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ECOLOGICAL ASPECTS OF THE NUCLEAR AGE: SELECTED READINGS IN RADIATION ECOLOGY

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ECOLOGICAL ASPECTS OF THE NUCLEAR AGE:
SELECTED READINGS
IN
RADIATION ECOLOGY

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1972

DEDICATION

Dr. John N. Wolfe, first chief of the Environmental Sciences Branch and first ecologist of the Division of Biology and Medicine, U. S. Atomic Energy Commission, to whom we are all indebted.

PREFACE

The last few years has been a period of public concern for environmental pollution, its health hazards and its effect on the quality of life. The impact of the nuclear age on the health and safety of man has been of public concern for many years; however, it is only recently that the non-professional has expressed concern as to effects on the environment. Unfortunately, nuclear testing, peaceful uses of the atom and consequent impact of such activities on man and his environment are relatively poorly understood by many. This selection of scientific literature has been compiled in the belief that an informed, aroused public is much more desirable than one which is sometimes uninformed and belligerent.

Admittedly our knowledge of the fate and effect of radionuclides in the environment is incomplete; however, a considerable literature does exist. Unfortunately, it is scattered rather widely. It is our purpose in compiling these Selected Readings to bring together, where possible; first, relatively recent summary papers in the field of radiation ecology; second, studies involving populations, communities or ecosystems and; third, some papers of historical interest. As much as we regret it, the inclusion of many excellent non-summary papers was impossible; however, we have included a few of these in Additional Readings. Consequently, publications of many excellent, active radiation ecologists do not appear in this compilation, and particularly our foreign colleagues are neglected. Difficulties inherent in searching the world's literature has resulted in emphasis of the English literature, including translations into English. We extend our apologies for this to our colleagues, particularly the Russians and French. Further legal restrictions, size and cost of reproduction precluded selection of some references; however, these are listed in Additional Readings. Our format consists of subdividing the readings into major subjects and within these parts including a Preface, reproduction of Selected Readings and a list of Additional Readings. In our selections we have attempted to cover terrestrial, freshwater and marine environments. The Additional Readings are presented in alphabetical order while the Selected Readings are in a suggested reading order. For the reader desiring to familiarize himself with the literature of radiation ecology we have appended a list of the major bibliographies, proceedings and books directly related to the subject.

Acknowledgments are due Carol J. Grimes, Janis G. Infanger, Alice E. Peters, Sandra L. Schultz and Francie L. Wright for secretarial assistance; Robert F. Pigeon and Charles R. Bruce, Division of Technical Information, U. S. AEC, for encouragement and technical assistance; S. I. Auerbach, K. Cowser, A. W. Klement, Jr., T. R. Rice, A. H. Seymour, G. M. Woodwell for comments and suggestions. Last but not least we are grateful to the authors and publishers for allowing us to reprint these papers, many of which are copyrighted.

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PART I. SCOPE, STATUS AND NEEDS OF RADIATION ECOLOGY

Preface

Radiation ecology can be considered as a field of endeavor which encompasses the relationships between radiation or radioactive substances and the environment, or sub-units within the environment such as populations, communities and ecosystems. The primary relationships between radiation and the environment include: (a) movement of radionuclides within ecological systems and accumulation within specific ecosystem components such as soil, water, air and organisms; (b) effects of ionizing radiation upon ecological systems and component populations and communities; and (c) use of radioactive materials and radiations in studies of structure and function of ecosystems and their component sub-systems. Although radiation ecology is concerned firstly with radioactive materials as environmental contaminants, factors, or tools, the implications of research findings in this field are usually very broad and extend to many other toxic substances which affect environmental quality.

Because radiation ecology involves numerous scientific disciplines, it is ordinarily considered to be interdisciplinary rather than discrete. Workers in radiation ecology have extremely varied backgrounds, normally encompassing one or more life sciences and several physical sciences. Fundamental to studies in radiation ecology is some knowledge of the properties and measurement of ionizing radiation. Also, since life has evolved in a natural radiation environment of incessant bombardment by cosmic rays and radiations from primordial radionuclides in the earth's crust, it is often necessary to consider added radiation in relation to natural background levels.

Because of the tremendous complexity involved in the behavior and effects of radionuclides in the environment, and because of the very young nature of the field, there is much to be learned. In spite of the fact that the body of knowledge in radiation ecology has made impressive gains, especially in the last decade, pressing questions exist which cannot as yet be answered with certainty. It takes time, often years or even decades to understand ecosystems in their normal and stressed conditions. We cannot expect quick, simple answers to such complex questions.

SPECIES RESPONSE TO RADIATION; RADIOECOLOGY*

*By Ralph Buchsbaum, Dept. of Biological Sciences, University of Pittsburgh, Pittsburgh, Pa.

I. Introduction

All living organisms, always, from the time of their origin on earth until now, have been irradiated. And in the future, everywhere, they will continue to be irradiated. Some of the radiation, from the sun, is necessary for continued life; some of it is unnecessary; and some is harmful. It is extremely difficult to sort out the various effects and to decide what is factual and of significance; it is much more difficult to sort out the good, the indifferent, and the bad effects among the known phenomena of environmental radiation. A great deal of work will have to be done before we can write an adequate theory of environmental radiation. But some progress has been made in the recognition of problems and in the analysis of factors involved in environmental radiation, or radioecology. A review of the problems, some of the factors concerned, and the progress made in this study will be presented here.

Two questions will be discussed. First, what are the effects of radiations on species of plants and animals in natural communities, or ecosystems (rather than in laboratory-controlled situations) under various levels of radiation? Second, what progress has been made in specific ecological studies in communities under radiation stress?

II. Radiation and Ecosystems

All living organisms are ecologically related to one another. With respect to radiation, in any given community, they are interrelated because they coexist in the same area and are subject to the same potential over-all external radiation, with the very important qualifications to be noted, for example, with respect to habitat. They are also related to each other in the total physiology of the community. Such an assemblage of organisms in a restricted locality is known as an *ecosystem* [see Allee et al. (1) and Odum (2) for a full explanation of this concept]. This is the chief unit of ecology. The energy used by all of the individuals, first captured from sunlight by the green plants, inti-

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Buchsbaum, R. 1958. Chp. 5. Species response to radiation: radioecology. pp. 124-141. In: Radiation Biology and Medicine. (W. D. Claus, ed.). Addison-Wesley, Reading, Massachusetts.

mately ties together all organisms in the ecosystem through steps in food chains or, more accurately, food webs, because a particular species may have a role in several food chains. If radioactivity in the form of radioisotopes is introduced into any individual plant or animal or into the physical environment, it will appear sooner or later—usually sooner—throughout the ecosystem. Its effects will depend not only upon the physical properties of the radioactive material but upon the handling of the radioactive material by the community.

An ecosystem is not just an assemblage of plants, animals, and microorganisms which happen to live in a given region and tolerate the climate. The importance of the ecological community is that its members are dependent upon one another and in most cases could not live without one another. The role that each species of organism plays in a community is important in tracing the effects of radiation.

5–1 Niches of animals or plants in the community. The role or function or, ecologically speaking, the *niche* of an animal or plant in the community may be put into one of several major classes [see Buchsbaum (3) for a fuller discussion of the niche concept]. The chief niches in any community are as follows: (a) The *primary food producers,* the green plants such as the trees in an oak forest or the grass in the grasslands. The principal food producers are also known as the *dominants,* since they take the full impact of the climate and set the stage for the remainder of the community. They modify the microclimate and set the tone for the animals and other plants that live there. (b) The *primary herbivores* or key-industry animals, which feed on the primary food producers and turn plant material into animal material. Examples are the plantlice in a grassland, mice in a meadow, or copepods in the sea. (c) The *basic carnivores,* which feed on the primary herbivores or key-industry animals, such as ladybird beetles which feed on plantlice in a meadow or small fish which feed on copepods in the sea. (d) *Higher-order carnivores,* such as small birds which feed on spiders in a meadow, or fish which feed on small fish in the ocean. (e) *Scavengers,* which feed on dead organic matter; examples are ants which eat almost any kind of dead material in a meadow, or hermit crabs which feed on dead organic matter on a seashore. (f) *Parasites,* which live in and feed on the bodies of other plants or animals, like the tapeworms of the pig intestine or the nematode worms in the leaves of plants. (g) *Decomposers,* which break down further the excreta and uneaten organic remains of plants and animals, such as the fungi, bacteria. (h) *Transformers,* such as those which fix nitrogen into soluble compounds in soil and water.

There are also specialized niches which are combinations or odd jobs, as it were, of the standard ways of making a living in a community. For

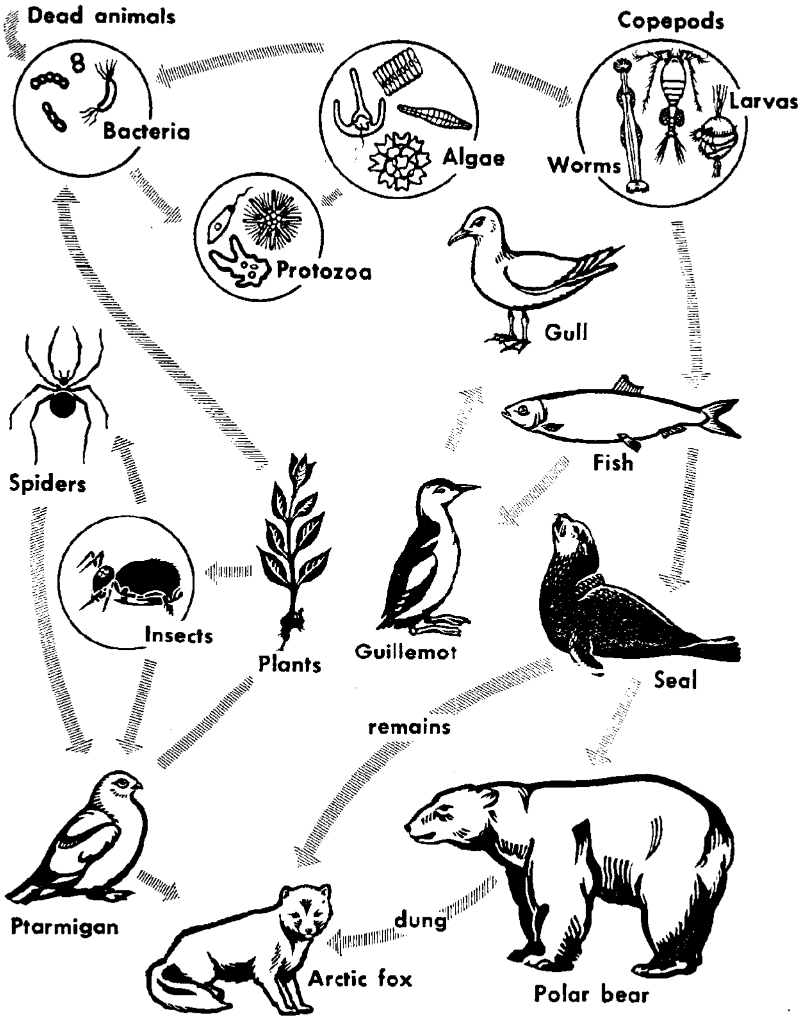
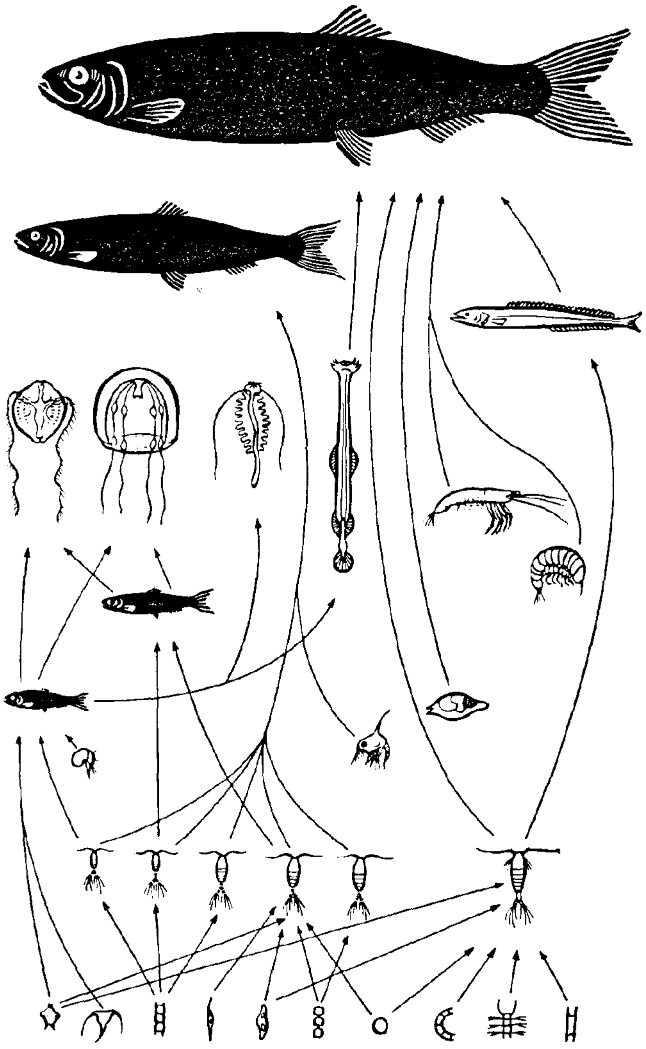


FIG. 5–1. Food web on Bear Island in the Arctic zone. Most of the food relationships are shown; however, there are many more species of protozoans, algae, rotifers, copepods, insects, birds, and fish. (From R. and M. Buchsbaum, *Basic Ecology*. Pittsburgh: Boxwood Press, 1957.)

On opposing page:

FIG. 5–2. Herring food web. The herrings are shown in solid black. Note that the smallest herrings are themselves eaten by (from left to right) the comb jelly, the jellyfish, the tomopterid worm, and the Sagitta or arrow worm. In the bottom



row are the microscopic plant plankton; above them, various species of copepods; next higher, the small planktonic larvas of snails, barnacles, and crabs, etc.; then the smallest herring, $\frac{1}{2}$ to $\frac{1}{4}$ inch in size; above this, a herring $\frac{1}{2}$ to 2 inches and crustaceans about 1 inch in length; above these, four larger animals (1 to 3 inches) of the plankton (including the comb jelly, etc.); then the sand eel, next the 2- to 5-inch herring; and at the top, the herring 5 inches and over. (From R. and M. Buchsbaum, *Basic Ecology*. Pittsburgh: Boxwood Press, 1957. Based on data of Hardy.)

example, the eating of ticks is performed by a bird in Panama and a crab in the Galapagos Islands.

The niche is therefore an important factor in radiation aside from size, habitat, kind of reproduction, and species susceptibility. The niche refers to the place of an organism in the food web, as mentioned above, and as shown in Figs. 5–1 and 5–2, of a food web on land and in the water. These two webs may overlap, and are in actual fact much more complex than could be depicted with any clarity in a diagram. In the context of radiation ecology, the arrows in the figures are read, "is eaten by and radioactive material is passed on to . . ."

The natural rhythm of day and night complicates the ecosystem, in that individuals of a species which occupy a particular niche during the day usually vacate it during the night. And because the niche is open, other individuals of other species usually can be found to do this particular ecological job at night. For example, hawks feed on meadow mice during the day and sleep at night; owls sleep during the day and feed on other species of mice during the night. If one finds a radioisotope in an animal which is active during the daytime, one must also look for its counterpart in the night fauna.

5–2 Radioecological significance of changes in community life. As the *seasons progress* around the year from winter to spring to summer to autumn and back to winter again, the familiar changes in the life of the community have radioecological significance. In the winter, in temperate latitudes, nearly all the community is in hibernation or dormant, even man is mostly indoors; radioresistance is at a maximum. With spring, growth and reproductive activity begin and continue in various species throughout the summer and early fall. During this period radioresistance is minimum. With the approach of winter, most of the community settles down into a minimum physiological activity for the winter. Some of the animals, notably birds, may migrate to far distant places to join other ecosystems and so transport radioactivity from one ecological community to another.

Long-time changes in communities take place as the members of the ecosystem gradually change the community by their activities, and aside from merely physical changes or geological processes. Sometimes organisms do this in such a way that they, themselves, can no longer tolerate the conditions which they have brought about. They then perish or migrate, leaving the changed conditions for other species more adapted to the now altered conditions. Or, put in another way, the early pioneering forms are driven out by new species. Such changes are known as *ecological succession* and they have been extensively studied in a variety of types of habitats [see Buchsbaum (3) for a fuller account]. Exactly

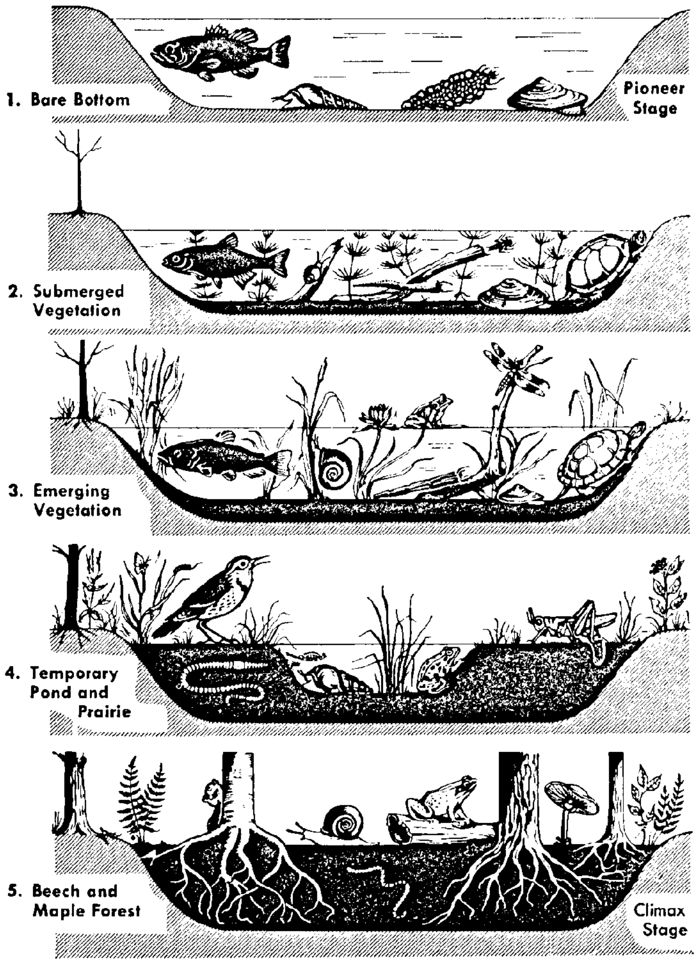


FIG. 5-3. Pond succession, simplified. The stages here are based upon events that are thought to occur in the ponds at the south end of Lake Michigan. Other ponds in the Middle West will go through much the same succession. The succession in ponds with a very different climate will be different in detail; and, of course, the climax will be different. Humus laid down since the beginning is shown in solid black. (From R. and M. Buchsbaum, *Basic Ecology*. Pittsburgh: Boxwood Press, 1957.)

what series of communities will succeed one another and what type of community will eventually come to equilibrium (the climax community) and continue to occupy a given region depends upon many things, but mainly upon climate and soil. Figure 5-3 illustrates ecological succession in a pond.

The dynamics of the ecosystem have radioecological significance. The specific effects depend upon the kind, quantity, and rate of irradiation. With low dose levels and long time exposure, the effect on succession may be one of modifying certain species more than others, and so altering the usually expected pattern of succession. No published studies are available to give us very much data on this point, but some of the studies on the White Oak River in Tennessee (4,5) on the Columbia River in Washington (6,7), and on the Savannah River in Georgia (8,9) may eventually be among the first to do so. With high-level radioactivity, as on bomb test sites, for example, a bare area is created and this is followed by pioneer species which invade it from adjacent areas. Bare areas of this kind may have residual radiation of various levels from high to very low. If the level of residual radioactivity is high, all of the dominants are probably dead or will die and the denuded area may suffer severe soil erosion. Eventually the region will become populated with pioneer forms. Depending upon what progress they make in modifying the area, they will, in turn, be succeeded by other forms, and so on through various stages until a climax is reached. The particular make-up of the climax will depend upon which species become established under the new conditions, which must include the factor of residual radioactivity. Where the bare area is a new artificial pond or lake, the succession likewise may not follow the usual pattern for the particular soil and climate, if the pond is to receive highly radioactive waste materials.

5-3 Natural selection and radiation. The mere survival of any one individual over another, of course, may be purely accidental and not at all related to over-all fitness. For example, when an earthslide covers a patch of forest, burying all life beneath tons of rock and soil, none of those buried may be said to have perished for lack of fitness. But, that fraction of a population, of bark beetles, for example, that withstands a winter, is likely to be by some degree more fit (at least to withstand the winter temperatures) than the fraction that perished. *Natural selection* is the name given to the force or combination of forces whose action results in the survival of certain types of organisms rather than others. Extending this reasoning to the general conclusion that those who survive are more adapted, or more fit (statistically at least), than those who do not is still the best working hypothesis of modern evolutionists.

In other words, natural selection is the guiding factor in evolution.

With this mechanism, and with radiation a factor which causes an increase in the rate of mutation, hence variation, one can predict that over a long time, there will be an increase in the species least damaged by radiation. Not only will the number of species of higher radioresistance increase, but some species of low frequency would become extinct. It would also be expected that some previously successful types may die out because of the increased burden of deleterious mutants, and that some previously unsuccessful types may now be favored in areas from which they were formerly excluded merely because of pressure from vigorous competition of a type now decreasing on the basis of high radiosensitivity (9–13). The composition of such a replacement ecosystem might be vastly different from a former occupant of the region. But there would be the same niches, and the same ecological principles would describe the community. It would simply mean that the usual niches would be occupied by different species.

In cultivated areas having large concentrations of one species there may be such losses as a result of high levels of radiation that new dominants may move in through the possession of some, ever so slight, advantage with respect to survival. For example, unusual weeds may appear, and parasites of the weeds, now rare, may become novel pests as their host plants increase in number. This may be expected to pose new problems of control. Some of these problems are discussed in Part 8. Most of these statements are hypothetical and call for field experimentation (8).

5–4 Factors influencing radiosensitivity. *Temperature* is a physical factor which has an important influence upon radiosensitivity. While it will be discussed in more detail in connection with mutation and was discussed earlier in its physiological connotations, here it is mentioned in an ecological context. Temperature varies in the environment both seasonally and geographically, and organisms are affected by radiation depending upon the season and the location. Also, warm-blooded organisms (birds and mammals) are usually more sensitive to radiation than are cold-blooded organisms (14).

Susceptibility to irradiation is a complex thing, and even under standard conditions related species will differ enormously in radiosensitivity. The significant factors are not known, but they include very fundamental biochemical and cellular characteristics. *Species specificity* is discussed elsewhere in Part 2. However, a few examples here will emphasize the facts of difference, which include behavior differences.

Among plants, severe defects were noted [by Sparrow and Christensen, 1953, as cited by Odum (9)] in *Tradescantia* at a dose rate of 40 r per day for a number of weeks; in a hybrid gladiolus, 6000 r per day were required to produce the same effect. Among insects [Jenkins, 1957, as cited by Odum (9)], the screw worm fly (*Callitroga*) required 5000 r to effect 100 percent sterilization, while *Drosophila* required 16,000 r and the powder post beetle (*Lyctus*) required 32,000 r.

The *specific habitat* of a species is an ecological reason for variation in susceptibility to radiation. Quite obviously, an animal which spends most of its time in an underground burrow will be less likely to radiation damage from a source above ground than one which lives in trees and feeds on leaves. Bats, for example, may sleep during the day far underground in caves and fly out only during the night to feed on flying insects. Unless the insects are radioactive (which, of course, they may be), bats may escape radiation altogether, even solar radiation. Similarly, deep-sea forms may be thoroughly insulated from radiation, except where a radioactive isotope enters the body through the food chain or where they are exposed to radioactive wastes.

Another factor in species differences with respect to radiosensitivity is *size*. Two species which differ only in size will respond differently to radiation if one has its protoplasm dispersed into a great many independent single cells, as in bacteria or protozoans, and the other has its protoplasm concentrated into large aggregations of specialized interdependent cells. When irradiated, the single-celled species may suffer much damage as individual cell casualties, but on a statistical basis some may escape entirely and give rise to a new series of descendants. The multicellular species may suffer an equal number of cell casualties, but because of interdependence, every cell aggregation, i.e., every individual many-celled organism, may die. For example, if 99 percent of the individual cells of a bacterial culture are killed or sterilized by a certain level of gamma radiation, and similarly 99 percent of the cells of a multicellular organism are so damaged, only the bacterial species will survive. However, small size might increase the liability to destruction, depending upon the penetrating power of the radiation. For example, minute organisms such as protozoans, naked eggs, pollen grains, minute insects, or leaves would be more seriously damaged by β-particles than would mammals, which might suffer, at most, severe skin burns (15). Barring internal consumption, a heavy fall-out of a β-emitter such as strontium-90 might more likely kill off small species like grasshopper nymphs than large animals such as cattle, on the basis of size alone. If most of the individuals of a species of insects, for example, have laid their eggs and died, a few of the eggs, being very small, may escape radiation in some circumstances, and even though all of the adults may be killed the species may survive. On the other hand, the same insect species, under the same conditions, exposed to a uniform high level of radiation might be better off in the adult condition, since the chitinous exoskeleton of the body wall may effectively shield the living cells within, including the eggs.

The innumerable combinations of circumstances make the subject enormously complex and difficult to study. These facts emphasize the need for direct, controlled radioecological experiments.

Just what the biological effect will be will depend, of course, upon the particular radioisotope, its half-life, its activity, its biological half-life, and its biochemical characteristics in the physiology of the organism. This is not a topic to be discussed here, except to indicate that, of course, the concentration of the nonradioactive isotope is significant. The addition of P^{32} to a lake with a high natural phosphorus content will result in organisms taking up less P^{32} than in a lake low in phosphorus. Similarly with Sr^{90}; contamination of a calcium-rich soil with Sr^{90} produces less radiation damage than the same concentration of Sr^{90} in a soil poor in calcium (15).

5–5 Comparative resistance of various species to radiation. Asexual species, such as certain flagellates and amebas, are frequently much more resistant to radiation than sexually reproducing species, not only because of the size principle, but also because of the population effect. A few of the less injured individuals may quickly reproduce (by cell division) to restore the population, and in especially favorable circumstances the population may be restored in a few days or weeks. The large asexual organisms are all plants: no large animals reproduce asexually. Sex involves a special complex cell division, known as meiosis, to produce gametes. In meiosis, the chromosomes (bearers of the genes) pair off and separate, one member of each pair going to one of the gametes (egg or sperm). Meiosis takes place only in the reproductive tissues, and if these are irradiated the individual may become sterile. How this comes about is discussed in Section II of Chapter 8. In species which reproduce asexually as well as sexually, and this includes most of the lower animals and many plants, reproduction may take place from any of a large number of spots on the body of the parent. The probability that some of such buds or sprouts may not be damaged by a burst of radiation is higher than the probability that the gonads of a similar sexually reproducing organism may not be damaged. Hence, asexually reproducing organisms are more likely to survive radiation than sexually reproducing forms, other considerations aside.

Further, in a sexually-reproducing form, it is not necessary to kill off all individuals to produce extinction. If the total number of individuals is drastically reduced in a given locality, the probability of mating may be so low that reproduction does not take place at a sufficiently frequent rate to replace the population, and so the species may become extinct. On the other hand, with vegetatively reproducing species, a single individual may repopulate a given area.

Certain other considerations, suggested above, might reverse the survival picture under long-time low-level radiation because sexually-reproducing forms permit a much greater opportunity for variation, and hence a more rapid evolutionary adaptation to the new ecological conditions expected in a disturbed community. Such adaptations may be anything from an increased biochemical radioresistance to a change in a protective outer covering, modified eating habits, or modified behavior.

Short-lived species, having a short generation time, have more frequent reproductive periods; consequently their cells undergo cell division during a greater proportion of their lifetime. Such species are more susceptible to radiation damage than long-lived forms with infrequent reproductive periods, other factors aside. This conclusion is modified when combined with such other factors as species specificity and high body temperature. In the absence of empirical data, the exact radiological fate of a particular species is extremely difficult to predict.

Embryonic, young, rapidly growing stages in the life cycle are more radiosensitive than adult or old organisms (14,16). Ecologically, the operation of this rule tends to damage the young rather than the adult; hence a species is most vulnerable during the time it bears young. The LD_{50} for adult fruit flies (*Drosophila*) is about 10^5 r, while the corresponding value for the egg is close to 190 r (16). Similarly, adult barley [Mericle and Mericle, 1957, as cited by Odum (9)], like the adult fruit fly, can absorb a great deal of radiation without showing obvious somatic effects, while the embryo is sensitive to a few hundred r of radiation. The total community effect depends upon what proportion of each species is in a radiologically vulnerable stage. An ecosystem might survive massive radiation if it is received during the winter, but suffer enormously if it is received in the spring. And in contrast, the same ecosystem may perish if presented with chronic low level radiation which, though less in total energy, continued through a time when most of the species were going through their radiosensitive stages.

Plants are generally less sensitive to radiation damage than animals. However, when they do reproduce, their gametic products, e.g., pollen, may be even more exposed than those of many animals whose gametes are transferred by coitus. However, internal β-emitters may more thoroughly irradiate animal gametes than plant gametes because of the intimate association of the blood with reproductive tissues. In general, we may say that the larger herbivorous mammals are most vulnerable to radiation for several reasons: they have high body temperature and are large, herbivorous, sexual, and exposed to the open air practically all of the time. Next sensitive are the smaller mammals and birds, herbivorous insects, filter-feeding aquatic invertebrates (which, as we shall see, concentrate radioactive chemicals), higher plants, lower plants, unicellular animals and plants, bacteria, and viruses, in that order. Man, as an animal, ranks in radiosensitivity among the larger mammals. Man as a member of the ecosystem is somewhat less radiosensitive because he knows (or some individuals of this species know), in theory at least, how to protect himself. As a species, man has the capacity to avoid the problem altogether!

III. STUDIES IN RADIOECOLOGY

Two kinds of studies are needed in order for us to understand the effects of radiation in natural communities and to develop an adequate theory of radioecology. First, we should continue the study of normal nonirradiated areas—that is, with no more radiation than now exists. This is necessary to establish a base line, or a control level. Second, before any new atomic establishment is put into actual operation, a thorough ecological study should be made of the surrounding region and the study continued on a comparable level after the facility is operating. It is likely that living species are better indicators of radiation effects than our limited theory supplied with very nice data from refined instrumentation. In other words, while our instruments can detect very small amounts of radioactivity, such data have no meaning in terms of what radioactivity does to living things over a long period. Only by observing the community can we tell what the effects of radiation actually are under natural conditions.

On the practical side, interesting applications of radiation may appear with particular reference to agriculture, game management, and entomology, topics which are discussed in Part 8.

More important than mere radiobiology, in the long run, is our basic need to understand the operation of various factors of evolution and ecology not only as revealed by populations of particular species under laboratory-controlled conditions, but as they occur in nature. The need to know about radioecology will provide a useful stimulus to the greater goal. Two specific studies, one in water and one on land, will be reviewed briefly to show what type of work has been done in radioecology and, from the obvious gaps in our knowledge, what needs to be done to more fully understand the radioecological implications of the age of atomic fuels.

From 1950 to 1953 an ecological study was made (4,5) of White Oak Lake in Tennessee. This lake, made by damming White Oak Creek, receives some of the low-level radioactive effluents from the Oak Ridge National Laboratory. These wastes include fission products, uranium, and transuranic elements. In part, the radioactivity is induced radioactivity from the processing of various substances in isotope preparation. It was unfortunate that the investigators were not able to make a study of the ecosystem before the Oak Ridge establishment was set into operation [Tsivoglou strongly urges this point (17)]. This early oversight is now being avoided in the case of new reactor sites and more adequate precontamination studies are now being made.

A physical and chemical survey of the lake was made, together with a survey of the plant and animal plankton, the bottom fauna, the fish, and some shore plants and animals, including amphibians, reptiles, birds, and mammals. It was impossible to study all the biological groups in detail, hence representative or key organisms in the food web were selected.

There were no unusual conditions seen in the vegetation. The highest degree of radioactivity was found in plants nearest the laboratory and this fell off with distance; good autoradiograms were obtained from leaves after an exposure of 24 to 70 hours. There was no darkening of film from plants below the dam after an exposure of seven days. The highest concentration of radiomaterials in the woody plants was in the bark, and there was a decrease in radioactivity from lower parts of the trees toward the tops. Such tissue contained from 10^{-3} to 10^{-5} $\mu c/g$ of radioactivity. The soil contained 10^{-2} to 10^{-5} $\mu c/g$. There seemed to be no apparent correlation between the amounts of radioactivity in the soil and that of the plants. Plants selectively concentrated certain radionuclides, most commonly strontium, cesium, ruthenium, rare earths, and zirconium. Only one plant, an American elm (*Ulmus americanus*), selectively concentrated enough radiomaterial (radioruthenium) to cause any obvious structural damage; the edges of the leaves curled and died. But, in general, the morphology of the plants appeared normal in every respect. The ecological successions among the various species of plants around White Oak Lake and Creek showed no noticeable differences from those at similar sites near other reservoirs in the region.

The water of the lake increased in radioactivity during the three-year period, with more radioactivity appearing at the upper end than at the lower end, farthest from the laboratory. Radioactivity also increased from the surface to the bottom of the lake.

The plankton behaved as it usually does in such a lake, with a nitrate concentration of as much as 10 ppm, in that it showed a bimodal curve with peaks in the spring and fall. The species composition was similar to that in nearby lakes.

Blooms or pulses occurred which lasted from two days (*Chlamydomonas*) to more than a month (*Volvox*). Some pulses were local; others were dispersed over the entire lake. Some of the genera which made up the pulses were *Volvox*, *Euglena*, *Chlamydomonas*, *Difflugia*, *Cryptomonas*, and *Oscillatoria*. The most spectacular bloom was that of *Volvox* in which some samples contained more than 700,000 colonies per liter and had an activity of 1.4×10^{-2} μc/g. If half the radiomaterial in the plankton and only one percent of that in the water was radiophosphorus, the plant plankton concentrated this element from 100,000 to 285,000 times. One entire mat, more than 2000 pounds in weight, was estimated to contain 100 millicuries of radioactivity.

The littoral bottom fauna included larval dragonflies, damselflies, and other aquatic insects; midge larvae (*Tendipedidae*) were the most abundant. The sublittoral bottom fauna consisted largely of *Tubifex*, larval *Tendipes*, and the midge larva, *Chaoborus*. The region of highest contamination had only half as many genera as in uncontaminated parts of the same stream system. The reduction of productivity was only partially due to radioactivity, since there was heavy sedimentation along with the radioactive waste discharge. It was found that some of the organisms concentrated the radiophosphorus by factors greater than 100,000. No deleterious effects were noted among the species examined.

The vertebrates of the region were also studied. There were 23 species of fish, 14 of amphibians, 17 of reptiles, 158 of birds, and 16 species of mammals. There was evidence that two species of fish, the white crappie (*Pomoxis sparoides*) and the redhorse (*Moxostoma erythrurum*), were disappearing from the lake. The total radiation dose rate received by the fish was at least 57 rep per year from external radiation and probably several times that amount from internal radiation. There was evidence that the fish population was suffering from a slowed growth rate, as much as 25 percent for the black crappie (*Pomoxus nigro-maculatus*) and largemouth black bass (*Micropterus salmoides*) for example, and that they were suffering from a shortened life span. The black crappies generally concentrated greater amounts of radioactivity in the hard tissues, in a ratio of about 5 to 3, than did the bluegills (*Lepomis m. macrochirus*); the bluegills concentrated more radioactivity in the soft tissues, in the ratio of 3 to 2, than did the black crappies. In both species, the skeleton accumulated about 50 times more radioactivity than the muscle. The seasonal radioactivity is seen to vary with the temperature (Fig. 5–4). Both species selectively concentrated radiostrontium in amounts 20,000 to 30,000 times as great as the concentrations in the water in which they lived. Even though the stomach contents of the bluegills were more radioactive than those of the crappies, the crappies accumulated more radioactivity in hard tissues than did the bluegills.

The bullfrogs did not accumulate large amounts of radioactivity, but the turtles did. The snakes had very small amounts of radioactivity. The herons were not very radioactive, but the migratory waterfowl carried an average of 5 μc of radioactivity, mostly P^{32}. More than 6500 migratory waterfowl visited the lake in one season.

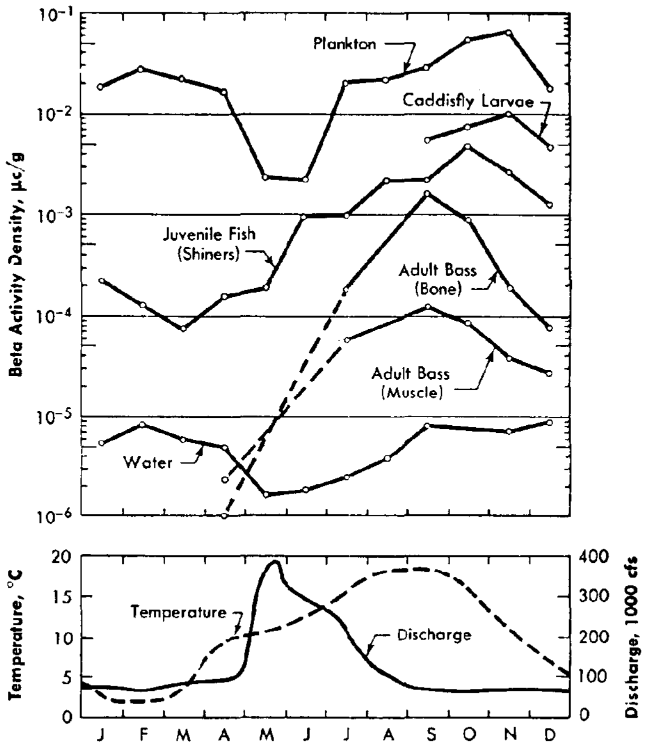


FIG. 5-4. Seasonal variation in average concentration of beta emitters in small-mouth bass, food organisms, and water in the Columbia River during 1952. River discharge and temperature are shown for comparison. Background activity for Columbia River water is about 1 × 10^{-8} μc/mm and for organisms, about 1 × 10^{-6} μc/gm. (Reference 6)

Among the mammals, muskrats and woodchuck accumulated more activity than the raccoons and squirrels. One muskrat had more than 1 μc Sr^{90} per gram of bone, a total burden of nearly 100 μc (18). That animal had developed an advanced osteogenic sarcoma at the proximal end of the right tibiofibula, and tumor cells had metastasized to both kidneys and lungs.* The authors emphasize the immense number of factors that must be taken into account in any over-all assessment of ecological changes that may take place, but point out that there was some evidence of a deterioration of the over-all fitness of the populations.

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*D. G. Watson at the Hanford Laboratories found that a concentration of 65 μc P^{32} per gram of bone was lethal to trout in about six weeks. A concentration of 10 μc per gram of bone caused some radiation damage [cited by Krumholz and Foster (19)].

The total radiation dose received by any of the organisms in White Oak Lake is not known. However, it may be estimated that if the average concentration of radioactivity in the water is 10^{-3} $\mu c/ml$ and the average effective energy is 0.3 Mev, the external dose rate is 1.1 rep per week. Some of the long-lived aquatic vertebrates such as fish probably received more than 50 r of external radiation per year during their entire life spans. In addition, such animals concentrate radiomaterials internally in an amount which yields a greater total internal radiation than that received externally. Plankton organisms have a very short life cycle full of reproductive events, but the effect of this radiation on them is not known. Information is needed on the fecundity of adults, viability of zygotes, and other radiobiologically significant data. Krumholz and Rust recommend, wisely, that the effects of radioactive effluents on wild populations of both vertebrates and invertebrates (and this author suggests plants, as well) should be continued on a long-term basis.

At the AEC Savannah River Plant in Georgia, a thorough ecological study is being made by Odum (9) prior to the release of radioactive materials.* The effort is being made to study the basic ecology of total ecosystems, with emphasis on food chain energy transfers and natural rates of ecological change. One of the most intensively studied communities is abandoned fields, which have the advantages of being taxonomically simple and of resembling the unstable type of ecosystem that is of most concern to man. The details of this important base line are not important to us here, but as the radioactivity accumulates, a long-time follow-up should give us information on the radioecology of such communities that will be of inestimable value. A second approach being made by Odum in the same area is that of measurement of the level of key or "index" animal populations. Experience with industrial pollution has shown that one cannot rely on single species as indicators, hence it is not safe to assume that a particular radiation-sensitive species might be found. However, it may be that populations of particular species, or perhaps whole ecosystems, might be very favorable as sensitive indicators of long-term radioecological effects. Again it should be emphasized that the contribution of such studies to the pure science of ecology will probably prove to be the most significant part of the undertaking.

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*In 1957 the AEC report is stated by Odum to indicate that 9×10^9 gallons of liquid wastes with 2×10^6 curies of radioactivity are now being discharged into rivers, the sea, and the soil. Waste disposal is now a rather insignificant task, but it is almost certain to be a major limiting factor in the production of atomic energy in the next decade. This problem will grow, and such pioneer radiation ecology studies as the one just reviewed at White Oak Lake and now this one at the Savannah River Plant, as well as others now beginning, are increasingly urgent.

IV. RADIOECOLOGY—CONCLUSIONS

The following general conclusions may tentatively be drawn.

(1) Atomic catastrophe, through blast, fire, and lethal-level radiation, will kill large numbers of plants and animals, producing bare areas which are open to erosion, and will be followed by pioneer stages of ecological succession. What type of climax will finally result will depend upon the climate, the extinction of endemic species, and the production of novel mutants, first from existing pioneer types and later from types which invade from adjacent areas. Some species useful to man (crop plants and domestic animals) may deteriorate or perish. New species or races may arise which may become dominants.

(2) Long-time increases in levels of radiation would facilitate extinction of small populations and rare species of limited range, and would increase the rate of evolution through the production of novel mutants arising out of competition with those presently more dominant. Certain species, now perhaps somewhat suppressed by other more vigorous forms, may become successful because of the destruction of their more highly radiosensitive competitors. A possible consequence is the evolution of more radioresistant types.

(3) Ecological research should be planned to precede and follow the installations of atomic energy establishments in order to develop an adequate body of data upon which to base a theory of radioecology and to advance the science of ecology generally.

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RADIOECOLOGY

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The new branch of science called radioecology received its name independently and simultaneously in 1956 in the two leading atomic powers of the world - the Soviet Union and the United States. Characteristically, it is in these two countries that ecology has developed more rapidly than elsewhere. This emphasizes the need of paying special attention to the reasons why the new branch came into being and is now progressing.

The main reason for the rise of radioecology is the anxiety felt by society at the increasing pollution of the atmosphere, vegetation, soil, and water by radioactive substances of industrial and military origin, whose effects on the biosphere can be judged both from the standpoint of their chemical toxicological significance and, more importantly, from the standpoint of their biologically potent and specific physical properties.

In its effects on the biosphere radiation from radioactive contamination has become a universal ecological factor, whose significance may often be incomparable greater than under the conditions of fluctuations in the natural radioactive background.

The significance of radioactive contamination is enhanced by the fact that it intensifies the external effect of ionizing radiation on the organism and that the organism can absorb many radioactive isotopes from the environment and selectively concentrate them in various organs, tissues, and cells, resulting in much more powerful irradiation of living systems. Radioactive decay of certain radioactive isotopes within the body produces radioactive and nonradioactive daughter isotopes of other chemical elements. This causes additional internal irradiation and injury to the chemical nature of complex, vitally important biochemical structures of the nucleus and protoplasm due to newly formed atoms which the organism neither obtained from its habitat nor used in similar forms when building its own structural elements.

Changes in biochemical structures induced by irradiation or by newly formed atoms lead to changes in metabolism, viability, adaptability, behavior, heredity, and size of population of a given species, all of which give rise to a variety of changes and reorganizations in biocoenoses. The biocoenoses, in turn, may influence the environment, which, along with study of environment influences, constitutes the very essence of ecology as a science concerned with the interaction of the processes linking the biosphere and its environment and with the processes that take place in the biosphere proper.

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The effect of biocoenoses on such sources of ionizing radiation as radioactive isotopes is most clearly manifested in absorption of these isotopes and in ecological food chains, which result in small and large biological migrations of radioactive networks, their concentration and dispersion, and in their shifting from contaminated to noncontaminated portions of the biosphere.

The influence of members of a biocoenosis on one another may be great not only as elements effecting the biological migration of radioisotopes, but in competitive situations and in situations favorable for storage of the isotopes in the body.

The aims of theoretical radioecology are to distinguish the types of ionizing radiation and to determine the laws governing the effect of different doses on populations and biocoenoses as well as to ascertain the types and laws governing the manifestations of the reverse effects of the populations and biocoenoses on radioactive isotopes.

The tasks of applied radioecology are extremely important and they will remain so long beyond the time when man in his technological, economic, and social development will be able to check the radioactive contamination of nature that is characteristic of our atomic age. The long-lived radioisotopes responsible for present-day contamination and the natural terrestial zones of high radioactivity will be modern man's legacy to posterity regardless of any social and technological changes that may take place. Therefore, one of the major tasks of applied radioecology will be to discover those elements and conditions whose elimination or intensification can help to control the biological migrations of radioisotopes so that they can come within the scope of our technical capabilities for providing safe burial. Applied radioecology is becoming increasingly important in the problem of efficiently utilizing zones of high radioactivity.

IMPACT OF ATOMIC ENERGY ON THE ENVIRONMENT AND ENVIRONMENTAL SCIENCE

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No new "age" ever had a genesis so suddenly emergent as has the era of Atomic Energy. And while the age does not belong exclusively to the Atom, it is and will be having notable ecological implications in the decades ahead.

Nor has any other "age" had the benefit of anticipating what might lie in the dim recesses of the future - to anticipate new environments, their hazards and their benefits, as has this age now aborning. This symposium is one of the evidences of this, and a good beginning it has turned out to be.

Almost from the time of his origins, Man has modified his environment by his agriculture, industry, recreation, and sometimes through sheer perversity. He has changed and/or removed soils systems, modified climatic patterns locally and regionally, and by introduction and destruction of habitat, he has brought proportional changes in the biotic composition of his living space.

Nor have all of these changes brought "growth" and "progress." As long as there have been new places to go in greater number than those abandoned, man has not cared, nor been aware of the insidious diminishment of his supporting environs - often accomplished to such a degree of destruction that recovery has been impossible in less than time periods of geologic magnitude.

The migratory agriculture in the tropics is a case in point. Occupancy of areas of tropical vegetation has brought high insolation and torrential rains alike to clearings, which set up processes of mineral leaching and put into accelerated motion the agencies of erosion. Soon the land is denuded and/or sterile, no longer able to support the plants that support man and his domesticated animals. Man's lone choice is the simple one of moving to another site and the cycle begins again.

Vast areas in North America's Southwest, subject to overgrazing and the blade of the plow, lost its productivity in massive clouds of dust in the 1930's. Not that the dust bowls became uninhabitable, but succession (or retrogression) proceeded from an equilibrium of grass and buffalo to man and grass and cattle to wheat and man and some cattle to horned toads and prickly pear cactus. And the latter populations are likely to be long persisting before that time in the milennia ahead when man and grass and cattle are at equilibrium with each other and the rest of the environment.

Other examples are multiple, and local examples are even more abundant. Man has and is changing the climate, soils and biota wherever he exists, but striking changes where he is gregarious are everywhere evident and almost always detrimental.

Climatic change is most evident and measurable in cities everywhere, and Los Angeles is but a single example; soils systems have been modified by

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drainage, wind and water erosion, and biotic practices. Where Southern aristocracy once reached its peak in Alabama's Black Belt, and furcate inflorescences of prairie bluestem fingered the skyline, Johnson grass now rattles its desiccated blades in the chalk-dust laden summer breezes, having been preceded by cotton as a terminal crop.

Now comes the atomic age, with its attendant new and immediate problems, not to mention those that are of a long-term nature. Problems are multiple at every level of biological organization, and in each of the seven major areas of nuclear energy effort, ecological understandings are important and immensely needed. To the timid who blanch before the nobility of biochemical and molecular biological research of the past decade; who are debating the relative merits of various biological research approaches; and who are awed by the splendor of space, the excitement of creating a primordial living system, it is appropriate to suggest that ecologists stick to their own lasts. The last assessment of experimental results in biology must be ecological, and the understanding of the environment and its working complex is likely to be essential to survival. For scientific and useful principles in replacing and juxtaposing biological materials over a landscape is as inevitable as it is ecological. What greater challenge! And it is not inappropriate to remark that before the chemist tells you why birds and butterflys and fish and mammals have homing proclivities, ecological data must tell him when and where. And while this may add to ecological pride, it really emphasizes the endless need to investigate life at all stages and levels of its systematic expression.

The Atomic Age thrusts upon man many questions with potential for both good and evil. Outlined only briefly below are areas of impact of the new power on man's environment.

1. Fallout: One of the unique characteristics of Atomic Energy is that its operations are not limited to local areas. Fallout from military testing is known to occur from pole to pole and even the fallout from stacks in the chemical processing plants transgresses the boundaries of the installations where they exist.

But I hasten to add that radioactivity at current fallout levels has produced very few recognizable somatic biological effects anywhere, including the Nevada Test Site and the Pacific Proving Grounds (and these at close-in areas). Mutants have not been found that could be attributed to radiation at fallout levels.

This is not to say that there have been no effects - simply that none has been found and intensive inquiry has been a part of the total research effort.

The low-level but detectable radioactive material, on the other hand, has considerable potential as a tracer in such studies as those involving meteorological phenomena in the stratosphere and below, oceanographic currents, fate of fresh-water emergence to the seas, geochronology, mineral cycling in natural and man-devised biological systems, food web patterns, micro erosion phenomena, and the redistribution and reconcentration on land and in the sea. Ramifications of these problems are innumerable.

2. Reactor Development: Base line studies at some proposed reactor sites are important, especially in the early years of this new source of power. In fact, biological researches could be useful in the selection of such sites.

The most formidable of the present ecological problems, however, is that of "waste disposal." Disposal of high level wastes in dynamic systems is strictly an ecological problem, not at all amenable to laboratory approach as are disposal of wastes from laboratories and medical establishments.

But in addition to the positive values (as in fallout) these materials require a long time view, and if reactors are to be productive over a quarter of half a century, much of their contribution to human environment has yet to be studied.

3. Wastes Disposal: Until such time as waste materials become useful byproducts in science and the economy, many problems must be faced with regard to

disposal. This is not simple in dynamic systems, and deep burial on the land, sea disposal, and dispersal in rivers all may have relationships to biotic systems. These all involve the techniques and research procedures of broad disciplines such as oceanography, hydrology, pedology, geology; and, in all, meteorological and climatological researches have roles to play.

4. Nuclear War: The devastation associated with international nuclear conflict is almost impossible to picture, and its total implications need not be outlined here. But ecological aftereffects on those who survive such attack present the major problems to existence. This aspect of ecological researches may be gruesome to approach, but it could possibly be essential to survival.

5. Technological Projects: The Plowshare program including such vast undertakings as harbor and canal excavations by detonation of nuclear devices requires a broad ecological perspective. The proposed engineering experiment in Alaska is an example; but it is only preliminary to such endeavors as a new canal at or near Panama and harbors or canals in other parts of the world. It would seem that researches in the biosphere before, during, and after such detonations would constitute a major contribution to a project that has been described as "geographical engineering."

Such studies, in fact, have a three-year accomplishment record in Alaska as this volume goes to press, and the studies indicate, on the whole, that such major projects at Ogotoruk Creek are feasible from a biological point of view.

But there is a warning to the technologists: Until conventionality becomes a characteristic of nuclear engineering methods - and even afterward in projects of great scope everywhere - sophisticated understanding and awareness of the importance of environment, physical and biotic, must match or exceed the values of the technical endeavors.

It is implied that technological planning along with bioenvironmental researches, short of nuclear conflict, are not inharmonious concomitant efforts.

And I would like to close with the strong inference that biological contributions to both geographical and local technologies provide essential scientific guidelines, useful perspective, and a modicum of culture to the total development of the planetary potential for human living and survival.

SUMMARY OF PART I

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Nuclear weapon explosions and the development of the nuclear power industry have led to the appearance of a new radioecological factor in nature. The concentration of long-lived fission products in the marine environment is continually rising and is, for example, 10^{-12} or even 10^{-11} Cur/l in terms of strontium-90 in the Irish Sea, into which radioactive wastes from the British nuclear plants are discharged, and in the Pacific Ocean, which has become a nuclear proving ground. Several countries are producing increasing quantities of radioactive wastes, and more and more attention is being paid to the seas and oceans as sites for disposal of these dangerous waste products. Some countries (the United States, the United Kingdom and France) bury radioactive wastes on the sea floor, in surface waters and in rivers flowing into the sea. The same use of the sea is planned by Sweden, Italy, India, Japan and other countries.

The systematic discharge of radioactive wastes into seawater from nuclear-power ships is now a permanent problem (Smith [1959]). Damage to nuclear reactors at sea and on the sea coast (e.g., the Windscale accident in 1957 and the fate of the American nuclear-power submarine Thresher in 1963) may have extremely significant consequences.

Artificially radioactive substances have therefore become a permanent radioecological factor in seas and oceans. This has led to development of a new branch of radiobiology: radioecology, whose task it is to study the features of the interaction between a radioactive environment and organisms, and thus to foresee the biological threat to life on earth, and to work out measures for the control of radiocontamination of the biosphere and the elimination of harmful consequences.

Marine radioecology, which is a major division of radioecology, should play an important part in studying the effect of radiocontamination of seawater on the biological and commercial output of the sea, in predicting the risk to human health of radioactivity contaminated marine foodstuffs, and in working out measures for preventing radiocontamination of the seas and oceans.

There are three basic research trends in marine radioecology: 1) systematic study of the content of artificially radioactive substances and their carriers in the most important marine organisms and in the environment in the various seas and oceans (analysis of the radioecological situation in nature), 2) experimental study of the accumulation and release of radioactive substances by plentiful marine organisms (prediction of the levels of accumulation of various radionuclides under natural conditions when they are present in certain concentrations in the sea-water) and 3) study of the biological effect of small doses of the radiation of various radionuclides on the vital processes, proliferation and development of marine organisms, on the structure and biomass

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Polikarpov, G. G. 1966. Summary of Part I. (The Subject Matter and Scope of Marine Radioecology). pp. 23-24. In: Radioecology of Aquatic Organisms. (G. G. Polikarpov). North-Holland, Amsterdam.

of their populations and biocoenoses (prediction of the threat to biological productivity and marine life of certain levels of radioactive contamination of sea-water). The first two aspects combined are one side of the theoretical problem of the interaction between marine organisms and a radioactive environment, namely the effect of aquatic organisms on a radioactive environment. Study of this matter will make it possible to establish the role of marine populations and biocoenoses in the migration and distribution of radioactive substances in the seas and oceans. The third aspect reflects the other side of this interaction, namely the effect of a radioactive environment on marine organisms. The alteration that this entails to the structure and biomass of populations and biocoenoses may, in its turn, lead to modification of the biological migration of radioactive substances.

Marine radioecology is faced with urgent practical problems of the nuclear age and with major theoretical problems. Radioecology, of which marine radioecology is a part, is therefore one of the most important theoretical and practical branches of present-day radiobiology.

FEEDBACK BETWEEN RADIATION ECOLOGY AND GENERAL ECOLOGY

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(*Presented by* E. P. ODUM)

Abstract—In an analogy with a feedback system it is suggested that symposia should function as "error detectors" as well as serve as sources of information for researchers. It is further suggested that the interdisciplinary field of radiation ecology is now ready to move from a primary preoccupation with techniques and description to a position of making major contributions to the theory of ecosystems. Radiation procedures offer powerful means for solving the twofold problem of ecosystems, that of relating the one-way flow of energy to the cycling of materials and of discovering how physical and biological factors interact to control the functioning ecosystem. Only by understanding these matters in depth can man act as his own error detector and correct for the perturbations caused by his own technology which increasingly tend to disrupt the organization of nature.

AT THE close of the First National Symposium on Radioecology held at Fort Collins in 1961 a panel discussion on education and research training was held.(1) It seems appropriate to begin my remarks prepared for the opening session of the present symposium by recalling the earlier panel discussion. Certain points discussed at that time are well worth reexamination as a prologue to the excellent series of technical papers that follows.

In 1961 there was a general agreement among the panel discussants that the designation "radiation ecology" was a convenient category to include the study of all aspects of ionizing radiation in the environment. Furthermore, it was agreed that the field of radiation ecology should not be thought of as a new discipline in the academic sense, but rather is best considered as an interdisciplinary field between established basic fields on the one hand and important applied fields on the other. As shown in Fig. 1 (reproduced from the SCHULTZ and KLEMENT's volume) three basic fields, namely ecology, geochemistry and radiation biology, and three applied fields, namely nuclear technology, environmental engineering and health physics were pictured as being especially important in the development of radiation ecology. Worrying about whether a new subject should be considered a new discipline or an interdisciplinary discipline is not entirely a matter of quibbling over words, because, I believe, a fundamental point of view is involved that may be important in programming for the future. For example, if our subject is to be promoted as a new self-contained field, then we should encourage the development of academic curricula, academic departments, college degrees, professional societies, specialized house organs (journals), etc. in radiation ecology as such. On the other hand, if radiation ecology is best served by an interdisciplinary approach, then we should discourage all the above mentioned developments, and, instead, encourage research programs, research institutes, special training courses, symposia and other mechanisms that encourage free interchange between the many established fields that have a contribution to

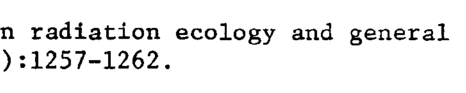

FIG. 1. Radiation ecology viewed as an interdisciplinary area between basic sciences (left) and applied sciences (right) (redrawn from ODUM in *Radioecology*(1)).

Odum, E. P. 1965. Feedback between radiation ecology and general ecology. Health Physics 11(12):1257-1262.

make to the area in question. Although the diagram in Fig. 1 does not by any means show all possible interrelationships, I believe it is a reasonable model of how the field of radiation ecology can best maintain its unique position in the complex fabric of modern science.

The great strength of an interdisciplinary field is that it remains an open system, with vigorous exchange of ideas and techniques between related areas of knowledge. It is especially important that a variety of thinking, approaches and technical skills be brought to bear on the very complex problems of radiation in our environment. As was also brought out in the 1961 panel discussions no pedagogic barriers should be erected that would arbitrarily limit the field when it is still in the formative stages of development. Too often in this age of increasing information and specialization new fields become too quickly compartmentalized, thus effectively discouraging both new ideas and new people from entering the field. I believe that radiation ecology has so far avoided this trap.

On the other hand there is a trap of another type into which an interdisciplinary field may fall. Lacking the self-perpetuation mechanism, as, for example, is provided by a specific professional organization, a new research area needs strong unifying concepts or centers of interest if it is to compete for personnel with well organized, established disciplines. During the past few years or so the excitment of working with radiation and radioactive materials and the urgent need to delimit the problems of radioactive fallout and waste disposal have provided the means of keeping a strong focus on the subject of radiation in the environment. We now need to broaden the base of our subject to give more attention to principles, and to the application of newly developed techniques to the solving of basic environmental problems. More vigorous feedback between ecology and radiation ecology than is now evident will be needed in the near future. The other disciplines as listed in Fig. 1 have much to contribute, especially in regard to technical advances. In the long run, however, we must look to ecology to provide unifying principles since ecology, more than any of the other established disciplines, is concerned with the fundamental relationships between the living and nonliving components of the ecosystem.

At this point let us consider the function of symposia such as the one we are now beginning. As just indicated, symposia are presumed to play a more important role in an open-ended interdisciplinary subject than in a compartmentalized subject where there are other professional devices for maintaining a strong motivation among the disciples of the subject. I think an analogy with a feedback system might be helpful in bringing out the points I wish to make.

A feedback system in its simplest form, as shown in Fig. 2, consists of two "black boxes", representing a "control device" and an "error detector", and a circle representing the "controlled quantity". In addition, an "energy source" is required for the control device while various outside unspecified perturbations, which in feedback parlance are often collectively known as "noise", impinge on the control quantity. Steering signals, control action, and the negative feedback between the controlled quantity and the error detector, are shown by the arrows in the diagram (Fig. 2).

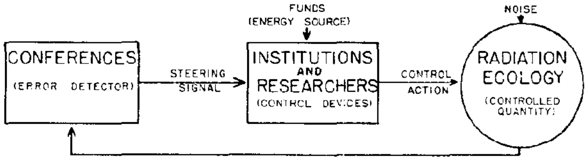

FIG. 2. A diagram of a simple feedback system as used in an analogy to suggest that symposia and conferences should function as error detectors in shaping the optimum development of interdisciplinary fields.

Now let us consider that "radiation ecology" is the object to be controlled in the sense that we want this field of study to continue to remain a vigorous and unique interdisciplinary area of investigation despite various "noise" factors that might tend to deflect its development from this charted course. Continuing the analogy as shown in Fig. 2, institutions and researchers become the "control devices" whose energy imputs are the funds received from the granting agencies or other sources. Finally, symposia and conferences are depicted as representing at least one type of the all important "error detector".

If, indeed, one of the functions of this symposium is that of an "error detector" then we shall expect that strong "steering signals" might be produced that will be picked up by researchers and administrators so as to correct "overshoots" (i.e. overworked areas) and to exploit "undershoots" (i.e. inadequately explored areas). As already indicated I believe one serious "undershoot" may be in the making in our lack of attention to the contribution that radiation ecology can make to the solving of basic ecological problems.

One thing is certain, any "steering signals" and "control actions" that come from this symposium will certainly result in very definite messages to the granting agencies calling for more "fuel" (i.e. funds) for the fires; I am sure that those persons attending the symposium who represent the granting agencies are already receiving plenty of signals of this kind!

The point of the analogy so far may be stated something as follows. Symposia, in addition to providing the individual with a critical summary of current knowledge, can also serve a useful purpose by pointing up, in a sort of negative feedback manner, the work that needs to be done to answer some of the big questions that tend to get lost in the pursuit of technical details. Probably the primary reason most of us attend one or more special symposia or conferences each year is to make up for the fact that for one reason or another we can no longer keep abreast by reading the journals, especially in fields which are developing so rapidly that it is important to know about unpublished or obscurely published methods and ideas. I believe it is high time that the second function of symposia, that of serving as "error detectors", be recognized by participants and organizers alike. As with all complex situations where human value judgement becomes difficult, I predict that conference organizers will soon be seeking the aid of computers to evaluate the impact of their symposia on the future progress of the field in question.

Now let us return to our theme that more ecology is needed in radiation ecology and vice versa. Recently I key-sorted from my punch-carded reprint collection those 1961–1964 papers which deal in whole or in part with some aspect of radiation and environment. Of the same 100 papers thus sorted out about 40 per cent deal primarily with methods, for example, development of field dosimiters or the use of a radioactive label to follow the movements of an animal. Another 40 per cent deal with the contributions that radiological techniques make to the understanding of ecological relationship, as, for example, the use of ^{14}C to clarify the relationship between nutrients and primary productivity. Only about 20 per cent of the papers could be said to represent contributions of ecology to the understanding of radiation in the environment, as, for example, the role of soil litter organisms in the movement of radioactive contaminants. Thus, it would seem that the exchange, shown as a two-way equilibrium in Fig. 1, has been mostly in the direction of radioecology → ecology.

It is quite understandable that technology should dominate the early development of a new field. I see nothing wrong with this provided the next logical step, that of using techniques to get answers to basic questions, is not too long delayed. As time goes on undue preoccupation with technology as an end in itself could develop into a real "noise" factor that could knock our subject out of its proper orbit.

To illustrate how difficult it is to mesh technology and principles, I would like to describe briefly the evolution of our feeble efforts to investigate, by means of radionuclide tracers, fundamental food chain relationships in terrestrial vegetation. We began with the theory that specific food chains could be isolated from other food chains in an intact ecosystem by labelling primary producers, one species at a time, and then observing the transfer of the label to higher trophic levels. Our studies were motivated not only by our desire to learn more about food chains in general, but also by the usefulness of the information on movement of tracers in predicting the fate of radioactive contaminants which might be introduced into man's environment. Thus, our studies have had both an ecological and a radioecological motivation.

The experiments to be described were carried out in old field vegetation at the AEC Savannah River Plant and in salt marsh vegetation at Sapelo Island and were supported by AEC contract AT-(38-1)-310 with the University of Georgia. In both places a variety of long-term ecological studies are in progress. A number of persons have contributed to these studies including E. J. Kuenzler, C. E. Connell, R. G. Weigert, Jay Schnell, T. G. Marples and J. B. Gentry.

In our first experiment a plywood box open at the bottom and fitted with a transparent plastic top and long rubber gloves was fabricated. The box was placed over 1m^2 of vegetation, and the tracer solution sprayed on the vegetation creating what we then termed a "hot quadrat"! While this method proved to be useful in determining the fate of "experimental fallout" the results were not satisfactory in terms of the original objective; the treated areas were too small and many small animals and the soil became directly contaminated as well as the plants.

In the second series of experiments, as reported at the 1961 radioecology symposium(2) single species of plants were labelled in separate large quadrats by applying droplets of tracer solution to leaf surfaces with a squeeze bottle or dropper. When activity density (disintegrations per min/mg) in subsequent samples of the animal populations was plotted against time it was found that trophic groups could be identified fairly well from the shape of uptake curves. As shown in Fig. 3, populations of active herbivores, such as grasshoppers or leafhoppers, tend to become highly labelled within the first week, whereas predators such as spiders, or detritus feeders such as millipeds, do not reach a peak in activity density until much later. Of several short-lived radionuclides tried, ^{32}P proved to be the most satisfactory for such food chain studies. However, the spot method of labelling was not very satisfactory, not only because the tracer did not become well distributed in the plant but also because a surprisingly large number of small insects were immediately attracted to the drops of solution and thus became directly contaminated at levels much higher than would result from food chain transfers.

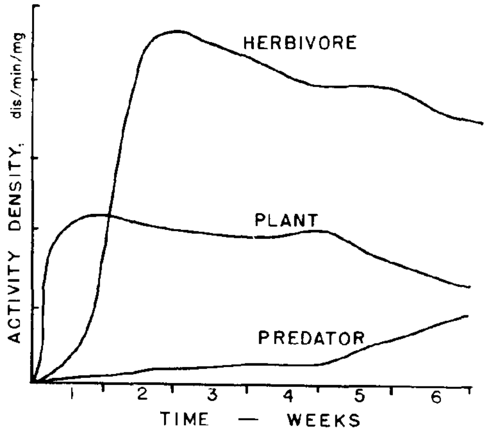

Fig. 3. Typical activity density curves at three trophic levels resulting from the labelling with ^{32}P (at time zero) single species of herbaceous plants in natural mixed stands. All curves corrected for radioactive decay.

In the third series of experiments, which constituted the doctoral thesis of T. G. Marples,(3) tracer solution was injected into the hollow stems of marsh grass (*Spartina alterniflora*). Satisfactory distribution of the tracer in the growing leaves was obtained and the direct contamination problem avoided. The injection method, however, is not satisfactory for most plants. ^{32}P proved a more satisfactory tracer than ^{65}Zn or ^{59}Fe although the latter, when introduced in the form of ferrous citrate, showed promise for situations where the desired study period might be longer than 6 weeks. By labelling living plants in one quadrat and the sedimentary detritus in another, Marples was able to determine which animals belonged primarily in the grazing food chain and which were primarily detritus feeders.

In the fourth series of experiments recently completed a "stem well" method of labelling old-field forbs was used.(4) This method was developed during class experiments at the first Radiation Ecology Summer Training Institute held at Oak Ridge in 1962, and is the most satisfactory one we have used so far.

In these last studies an attempt was made to apportion the tracer transfer, and thereby indirectly the energy flow, by species populations, and to estimate the grazing pressure exerted by insect herbivores on the two co-dominant forbs, *Erigeron canadense* and *Heterotheca subaxillaris*. These plants characterize early stages of old-field succession on the southeastern coastal plain.

As a tentative approach a "^{32}P transfer index" was calculated for each significant population from uptake curve data over 6 weeks study period as follows:

$$^{32}\text{P transfer index} = \frac{\text{mean activity density consumer}}{\text{mean activity density plant foliage}} \times \text{consumer biomass.}$$

Essentially, this is the mean concentration factor (C.F.) times the population biomass of the animal species in question. The mean activity densities can be calculated by averaging weekly values or, better still, from the areas under curves such as are shown in Fig. 3. In the case of herbivores a high index results from a high activity density plus a large population size and indicates that the insect population in question is relatively important in removing ^{32}P from the plant species in question. A low index results from low activity density and/or low numbers, and, therefore, indicates that the species is less important in terms of ^{32}P transfer from producer to consumer. In our experiments where the ^{32}P level in leaves was of the order of 1000 disintegrations per min/mg the most active plant feeders quickly reached and maintained an activity density two or three times this (hence C.F. = 2–3). Activity density for such predators as spiders did not approach that of leaves until near the end of the experiment (Fig. 3). Since uptake in predators was delayed and their biomass low, transfer indices were correspondingly low. Still lower indices were obtained for detitrus feeders reflecting the still greater delay in the transfer of the tracer.

Of the 124 species of insects collected in the labelled quadrats seven species of plant feeders accounted for most of the total ^{32}P removed from the plants, and only twenty-six species in all became sufficiently radioactive and were sufficiently abundant over a long enough period of time to play a measurable role in the nuclide transfer. This is in accordance with the general ecological theory that a few common species among a large diversity of rare species are likely to dominate consumer function in the early stages of vegetative succession. The cummulative index for herbivores was about ten times greater than that for predators, which is interesting in light of another ecological generality regarding a 10 per cent efficiency in energy transfer between the primary and secondary consumer trophic levels. Even more interesting was the completely unexpected finding that the herbivore cummulative index was about ten times greater for *Heterotheca* plants than for *Erigeron* plants even though the standing crop of both species was similar, both were actively growing at the time, and both were available to the same insect populations. In contrast, the common species of small ant exhibited a greater uptake from *Erigeron*. This suggests that *Erigeron* is attractive to ants but is somehow unattractive to grasshoppers, leafhoppers and other strictly phytophagous insects.

Thus we see that our experiments with radionuclide tracers have confirmed some ecological ideas, but have also revealed unexpected relationships that can not be explained as yet. Also, we do not yet know whether the ^{32}P transfer index is actually a good index of energy flow. Data on bioelimination, and on the relationship between nuclide uptake and food uptake, are needed before a definite correlation between our tentative transfer index and energy flow rates can be assumed.

Starting with a simple idea and passing through a necessary research stage that is preoccupied with techniques we have now arrived face to face with a central ecological problem, that of relating the one-way flow of energy to the cycling of materials in the intact ecosystem. It is most appropriate that the symposium we are about to begin is entitled "Radiation and Terrestrial Ecosystems" because this focuses our attention on the level of biological organization with which we must ultimately deal, namely, the ecosystem. Many will contend that we are not yet ready to take this level of organization because our knowledge of the component parts is so limited. Since organized units have properties that can not be explained entirely as the sums of the properties of component parts it is not too soon to come up to the ecosystem level, at least in our thinking. Furthermore, rapid expansion of human technology and the human population means that we will have to make some value judgements at the ecosystem level at the same time that we are pressing forward with studies at other levels of biological organization.

I believe we can safely say that principles relating to the ecosystem level are the most important ecological principles for those concerned with radiation and environment. The "systems ecology" which is beginning to emerge is an important focal point where strong feedback is needed between radiation ecology and general ecology.

The ecosystem is also a rallying point that can bring together the two major aspects of radiation ecology which, so far, have remained largely separate. I refer, of course, to the "fate" or "tracer" aspect and the "effects" aspect. As the mechanism of radiation effects at cell, organism and population levels becomes at least partially understood the way is opened for experiments on radiation effects at the ecosystem level. It is exciting to think about combining the use of tracers and radiation sources in the same experiment. Since tracers make it possible to detect very small changes in structure and in flux rates within an ecosystem, it should be possible ultimately to measure the effects of the very low radiation doses about which there is now so much controversy. In our program at the University of Georgia we are already thinking about the possibilities of introducing tracers into experimental microecosystems as well as into the larger field systems that are being subjected to radiation from gamma sources.

At the risk of oversimplification perhaps we can restate the central problem of the ecosystem as it relates to future work in radiation ecology. The problem is to discover how physical and biological factors interact to control the ecosystem whose function involves the one-way flow of energy, the recycling of matter and the homeostatic maintenance of an astonishing variety of organisms. Radiation procedures offer powerful tools of study since they make possible experimental modifications and observations that are difficult to obtain by any other means. Returning to our feedback model in Fig. 2 in a broader context, we might be so bold as to state that only by understanding these matters in depth can man act as his own error detector and correct for the perturbations caused by his own technology which increasingly tend to disrupt the organization of nature.

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Advances in Radiation Ecology

By J. Olson

Numerous discussions in *Nuclear Safety* and elsewhere have stressed the many possibilities for release of radioactive materials to man's environment. Geographic isolation, centralized controls, and many-times-compounded margins of radiological safety have helped to restrict the magnitudes of such releases. But isolation is diminishing, control responsibility is becoming decentralized, and changes, both for improved performance and lower costs, are being effected. Safety procedures are coming to depend increasingly on scientific knowledge of how radionuclides move and how ionizing radiation could affect man's environment. Radiation ecology aims to help furnish some of this needed knowledge and to use it for gaining better perspective on basic and practical environmental problems.

This first review in a series on radiation ecology (sometimes called "radioecology") will note the aims and scope of the field. The Proceedings of the First National Symposium on Radioecology[1] illustrate the scope and raise many questions. These questions and some answers will be covered further in later issues of *Nuclear Safety*.

Radiation Ecology and Radiation Biology

Eight areas of interest in radiation ecology and biology are described in Table V-1. Variations in emphasis on these and other areas will no doubt continue to reflect the individualistic curiosity and background of the investigators and the diverse programmatic needs of science and technology. The problem areas themselves support each other and intergrade.

In radiation biology (or "radiobiology"), the term "photophysiology"[2] has been used to separate studies of action of light and near-visible radiation (B1 in Table V-1) from studies of ionizing radiation (B2).[3] Problems of internal dose illustrate particularly strong ties between studies of ionizing radiation or its effects and the physiology of nuclide distribution within organisms and their parts (B3). Numerous applications of tracer methodology to biological questions, which have little to do with radiation per se (B4), occupy at least some attention of many radiobiologists. Opinions vary as to how far to extend the term radiobiology to encompass such diverse applications.

Ecology has analogous distinctions. It is concerned not only with the environmental relations of individuals and species but also with the problems of larger systems: populations and ecological systems (or *ecosystems*) that consist of sets of environments including organisms. Just as radiation biologists probe the fundamental processes and molecular components of life itself, radioecologists are exploring the fundamental processes and components that maintain organization on the level of populations and ecosystems (A4). The understanding of the circulation of nonradioactive nuclides in nature should help to reach beyond a narrowly empirical study of the movement of radionuclides in the environment (A3), while the power of tracers in turn helps to provide quantitative models of natural processes. Knowledge of the sources and distribution of radionuclides is prerequisite for evaluating possible effects of ionizing radiation on natural and man-modified ecosystems (A2).

Predicting and evaluating these effects under the complex conditions of nature calls for explicit study of the interaction of ionizing radia-

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Olson, J. S. 1964. Advances in radiation ecology. Nuclear Safety 6(1): 78-81;94-95.

tion with various other factors of the environment. Radiation ecologists are particularly interested in effects of light, encompassed in photoecology (item A1 of Table V-1), partly because of its interaction with ionizing radiation. Also many are interested in the fundamental significance of solar energy capture for the world's production of vegetation and animals, including man. Although the biophysicist and biochemist use radiation and tracer isotopes for probing photosynthesis and ensuing cellular synthesis, the ecologist and whole-plant physiologist use such tools for clarifying why the earth's actual capture of the sun's energy of nuclear fusion is so much lower than that which is theoretically possible. These problems seem at least as important in this increasingly crowded world as all the problems of nuclear fission.

Table V-1 COMPARISON OF AREAS OF INTEREST IN RADIATION ECOLOGY AND BIOLOGY

A. Radioecology	B. Radiobiology
1. *Photoecology:* transfer of light (and infrared radiation) in ecosystems, with implications for productivity of plant-animal communities	1. *Photophysiology:* transfers of photons within organisms and their effects on photosynthesis and regulation of growth and stimuli
2. *Ecology of ionizing radiation* as one of many environmental factors affecting populations and ecosystems, as well as component species	2. *Physiology of ionizing radiation* on organisms and their parts, including biophysical-chemical mechanisms of radiation damage, recovery, and protection
3. *Environmental movement of radioactive nuclides* in landscapes and other ecosystems, with implications for external and internal radiation doses for members of plant-animal food chains	3. *Internal movement of radionuclides* among organs, tissues, and cells of animals and plants, with implications for internal dose and health physics
4. *Use of tracers and radiation* in basic and applied studies of the organization and activities of populations and ecosystems	4. *Use of tracers and radiation* in basic and applied studies of organization and activities of individual organisms and their many components

First National Symposium on Radioecology

Many topics are of interest to both ecology and nuclear energy programs. This was illustrated at the First National Symposium on Radiation Ecology (Fort Collins, Colo., 1961). The Symposium proceedings are available in a book entitled *Radioecology*[1] which will have permanent value as a compendium of useful reviews and initial research in several problem areas that were hardly recognized a few years ago. Later publications will no doubt pick up where this one stops, but they will probably never bring together so much interrelated background in a single cover. The 746 pages (double column, $16.50) include 86 papers and extensive bibliographies. (A second symposium is to be arranged at Hanford Laboratories in the spring of 1965.)

This review covers, principally, the general review papers in Part I of nine parts. The other eight parts will be mentioned briefly to illustrate the motivations and scope of radiation ecology.

General Review Papers

"The impact of atomic energy on the environment and environmental science" was outlined concisely in the keynote address[4] by Wolfe, Chief of the Environmental Sciences Branch of the AEC Division of Biology and Medicine, which sponsored the meeting and most of the work reported there. Among other things, he noted how major peacetime nuclear "geographical engineering" projects, such as the Plowshare proposals for Alaskan harbor testing or Central American canal excavations, can only be considered in a context of ecological perspectives on the biological impact of explosion and contamination. His further topics of weapon fallout, nuclear war, reactor development, and waste disposal all helped to show the need for more environmental research and were elaborated on in ensuing General Review Papers.

Larson's reviews[5] of "continental close-in fallout" tied together pioneering surveys of the late 1940's around the original Trinity bomb testing site in New Mexico with a compact synthesis of the more extensive Nevada Test Site studies of the 1950's. Some general conclusions on the strong adherence of fallout particles ($<44\,\mu$ and especially $<5\,\mu$) to vegetation discussed in an earlier *Nuclear Safety* review[6] fit with results from elsewhere in explaining the rather prominent effect of current fallout rates (as distinct from cumulative fallout in soil) on the amounts of fallout radioactivity in vegetation and animal food chains.

An implication here for accidents or civil defense on areas contaminated but not devastated by possible thermonuclear war is that many current crops affected by fallout might well be sacrificed because of surface contamination by mixed fission products. Crops growing in subsequent years might or might not carry significant concentrations of long-lived nuclides. Lane, Sartor, and Miller[7] recently compiled exchangeable calcium concentrations for dominant soils of each county in the United States as one parameter in their mathematical model for ^{90}Sr uptake. There are obviously other soil and biological parameters that would modify the predictions of contamination. For selection and hazards analyses of reactor sites, the evaluations of landscapes should depend on more specific local data.

Pritchard and Joseph[8] summarized the disposal of radioactive wastes, including both (1) the small but increasing volumes of high-level wastes, which already pose practical problems of shipping and "perpetual care," and (2) the large volumes of intermediate- and low-level water, which pose the greater problems of safe release into the environment. With the era of economic nuclear power approaching more rapidly than most people expected only three years ago, the ecological problems surrounding the local disposal areas will call for closer evaluation. Waste disposal and monitoring may no longer impose such a serious cost burden on each nuclear facility as was once feared. Development of methods to minimize escape to the environment and research to predict and follow the course of that which reaches the biosphere are growing obligations for nuclear energy programs.

In spite of spreading operations of reactors and processing plants, releases of environmental radioactivity have been moderate and have been kept within controlled areas (in accidents of category 1 of Guthrie and Nichols[9]; see also the discussion in the Sec. IV article by Guthrie and Nichols, page 57) or their immediate environs (category 2). Maximum credible accidents (category 3) and "incredible maximum" accidents (category 4) are not really expected to occur but are being scrutinized more closely in terms of guiding economics and insurance. The ecological ramifications of the unlikely large catastrophe, like those of the nuclear attack which it is hoped will never occur, have yet to be faced seriously.

Henshaw's comments[10] on "radiation effects and peaceful uses of atomic energy in the animal sciences" consisted mostly of a commentary on the nature of radiological damage. In spite of confusing terminology that is difficult to relate to usages in previous literature, this paper is thought provoking. Henshaw's considerations of life shortening are pertinent to the general philosophy of health physics, which must govern the use and restriction of radiation exposures in either defense or peaceful exploitation of nuclear energy.

The comprehensive review of Spikes[11] covered many "radiation effects and peaceful uses of atomic energy in the plant and soil sciences." Benefits from new knowledge in these fields were believed by some to have "already gone far toward compensating for the total initial investment of funds necessary for the development of atomic energy. These benefits will undoubtedly continue to multiply." However, a by-product of developing mutant varieties, and later of certain aircraft reactor programs, was the rather unexpected discovery that some widespread native plants (e.g., pine trees) are much more susceptible to radiation damage than had previously been anticipated. Ecological consequences of this discovery and the rapid advances at Brookhaven National Laboratory subsequent to the First National Symposium in 1961 will be considered in a later review of another section of the *Radioecology* volume.

Spikes emphasized the physiological and agricultural discoveries made with the use of radionuclides. The principles of nutrition and cycles of chemical elements are even more critical, however, in nonagricultural ecosystems, which have no fertilizer to remedy deficiencies in the low natural fertility of the soil or the unfavorable patterns of nutrient circulation. He concluded that "nuclear science offers one of the most powerful arrays of tools to ecological science that could be imagined. The applications are still primitive; it will be interesting to follow the developments in the future." Basic research exploiting the tools of nuclear energy will presumably repay its debt in by-products of ecological insight.

Other Papers

The rest of the *Radioecology* volume provides a sampling of the diverse interests already followed within radiation ecology. The largest single part (IX, 155 pages) on the "occurrence, effect and utilization of nuclides in the environment" consists of attempts to synthesize much of what is known on elements with significant radionuclides: Mn, Ru and Rh, W, Ca, rare earths, Cs and K, Ba, Fe and Co, Cr and Np, Zr, I, ^{3}H, As, Zn, Pu, and natural radioactive species. (Evidently the overwhelming burden of reviewing the effect of strontium was too much for any single reviewer to accept, but this element received its due share of attention throughout many other sections.) The reviews are as diverse as the backgrounds of the reviewers, but they generally include a good tie to the geochemistry of each element and to those implications significant for nuclear energy.

Additional papers that present current research on "cycling and levels of radionuclides" occupy the largest portion of the volume (A3 in Table V-1). They are divided among parts II to IV on terrestrial, marine, and fresh-water environments (98, 65, and 38 pages, respectively). Parts V and VI on "effects of ionizing radiation" in terrestrial and aquatic environments (107 and 47 pages) are of special interest in providing some of the first results on radiation effects on wild populations and communities of organisms (A2 in Table V-1). Parts VII and VIII on "ecological techniques" in terrestrial and aquatic environments (58 and 33 pages) illustrate several ways in which nuclides are used to trace movements of organisms and of materials in basic ecological research (A1 and A4 in Table V-1). Some of these results improve the understanding and predictability of radionuclides in nature and their eventual effects. Each of these parts of the Symposium, together with the more recent developments in each area, will receive more attention in later reviews.

Panel Discussion

In a panel discussion at the symposium on education and research training, "most discussants seemd to agree with the viewpoint that radiation ecology is best considered an interdisciplinary field and not a separate discipline as such... Whether a meeting (or pure science and the applied science) is best achieved by isolating a new speciality or by merely encouraging interchanges with already established specialties can be debated." Figure V-1 concisely indicates the desired flux of stimuli, information, and intellectual and administrative support between radiation ecology and fields such as geochemistry and nuclear technology, engineering and health physics, and basic ecology and biology. The present review suggests that little is gained, and some of the mutual benefits of this communication could be lost, by thinking of radiation ecology too rigidly and too narrowly as encompassing only effects of radiation (area A2 of Table V-1) or ecological problems of radionuclides as such (A3 and A2).

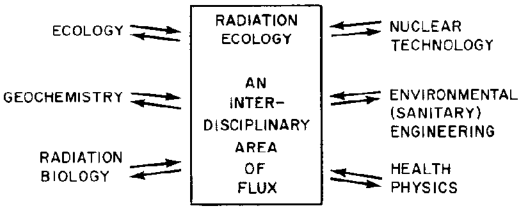

Fig. V-1 Radiation ecology viewed as an interdisciplinary area between basic sciences (left) and applied sciences (right). From *Radioecology*, p. 643, Ref. 1.

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Effects of Pollution on the Structure and Physiology of Ecosystems

Changes in natural ecosystems caused by many different types of disturbances are similar and predictable.

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The accumulation of various toxic substances in the biosphere is leading to complex changes in the structure and function of natural ecosystems. Although the changes are complex, they follow in aggregate patterns that are similar in many different ecosystems and are therefore broadly predictable. The patterns involve many changes but include especially simplification of the structure of both plant and animal communities, shifts in the ratio of gross production to total respiration, and loss of part or all of the inventory of nutrients. Despite the frequency with which various pollutants are causing such changes and the significance of the changes for all living systems (*1*), only a few studies show details of the pattern of change clearly. These are studies of the effects of ionizing radiation, of persistent pesticides, and of eutrophication. The effects of radiation will be used here to show the pattern of changes in terrestrial plant communities and to show similarities with the effects of fire, oxides of sulfur, and herbicides. Effects of such pollutants as pesticides on the animal community are less conspicuous but quite parallel, which shows that the ecological effects of pollution correspond very closely to the general "strategy of ecosystem development" outlined by Odum (*1*) and that they can be anticipated in considerable detail.

The problems caused by pollution are of interest from two viewpoints. Practical people—toxicologists, engineers, health physicists, public health officials, intensive users of the environment—consider pollution primarily as a direct hazard to man. Others, no less concerned for human welfare but with less pressing public responsibilities, recognize that toxicity to humans is but one aspect of the pollution problem, the other being a threat to the maintenance of a biosphere suitable for life as we know it. The first viewpoint leads to emphasis on human food chains; the second leads to emphasis on human welfare insofar as it depends on the integrity of the diverse ecosystems of the earth, the living systems that appear to have built and now maintain the biosphere.

The food-chain problem is by far the simpler; it is amenable at least in part to the pragmatic, narrowly compartmentalized solutions that industrialized societies are good at. The best example of the toxicological approach is in control of mutagens, particularly the radionuclides. These present a specific, direct hazard to man. They are much more important to man than to other organisms. A slightly enhanced rate of mutation is a serious danger to man, who has developed through medical science elaborate ways of preserving a high fraction of the genetic defects in the population; it is trivial to the rest of the biota, in which genetic defects may be eliminated through selection. This is an important fact about pollution hazards—toxic substances that are principally mutagenic are usually of far greater direct hazard to man than to the rest of the earth's biota and must be considered first from the standpoint of their movement to man through food webs or other mechanisms and to a much lesser extent from that of their effects on the ecosystem through which they move. We have erred, as shown below, in assuming that all toxic substances should be treated this way.

Pollutants that affect other components of the earth's biota as well as man present a far greater problem. Their effects are chronic and may be cumulative in contrast to the effects of short-lived disturbances that are repaired by succession. We ask what effects such pollutants have on the structure of natural ecosystems and on biological diversity and what these changes mean to physiology, especially to mineral cycling and the long-term potential for sustaining life.

Although experience with pollution of various types is extensive and growing rapidly, only a limited number of detailed case history studies provide convincing control data that deal with the structure of ecosystems. One of the clearest and most detailed series of experiments in recent years has been focused on the ecological effects of radiation. These studies are especially useful because they allow cause and effect to be related quantitatively at the ecosystem level, which is difficult to do in nature. The question arises, however, whether the results from studies of ionizing radiation, a factor that is not usually considered to have played an important role in recent evolution, have any general application. The answer, somewhat surprisingly to many biologists, seems to be that they do. The ecological effects of radiation follow patterns that are known from other types of disturbances. The studies of radiation, because of their specificity, provide useful clues for examination of effects of other types of pollution for which evidence is much more fragmentary.

The effects of chronic irradiation of a late successional oak-pine forest have been studied at Brookhaven National Laboratory in New York. After 6 months' exposure to chronic irradiation from a ^{137}Cs source, five well-defined zones of modification of vegetation had been established. They have become more pronounced through 7 years of chronic irradiation (Fig. 1). The zones were:

1) A central devastated zone, where exposures were > 200 R/day and no higher plants survived, although certain mosses and lichens survived up to exposures > 1000 R/day.

2) A sedge zone, where *Carex pensylvanica* (*2*) survived and ultimately formed a continuous cover (> 150 R/day).

3) A shrub zone in which two species of *Vaccinium* and one of *Gaylussacia* survived, with *Quercus ilicifolia* toward the outer limit of the

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Woodwell, G. M. 1970. Effects of pollution on the structure and physiology of ecosystems. Science 168(3930):429-433.

circle where exposures were lowest (> 40 R/day).

4) An oak zone, the pine having been eliminated (> 16 R/day).

5) Oak-pine forest, where exposures were < 2 R/day, and there was no obvious change in the number of species, although small changes in rates of growth were measurable at exposures as low as 1 R/day.

The effect was a systematic dissection of the forest, strata being removed layer by layer. Trees were eliminated at low exposures, then the taller shrubs (*Gaylussacia baccata*), then the lower shrubs (*Vaccinium* species), then the herbs, and finally the lichens and mosses. Within these groups, it was evident that under irradiation an upright form of growth was a disadvantage. The trees did vary—the pines (*Pinus rigida*) for instance were far more sensitive than the oaks without having a conspicuous tendency toward more upright growth, but all the trees were substantially more sensitive than the shrubs (*3*). Within the shrub zone, tall forms were more sensitive; even within the lichen populations, foliose and fruticose lichens proved more sensitive than crustose lichens (*4*).

The changes caused by chronic irradiation of herb communities in old fields show the same pattern—upright species are at a disadvantage. In one old field at Brookhaven, the frequency of low-growing plants increased along the gradient of increasing radiation intensity to 100 percent at > 1000 R/day (*5*). Comparison of the sensitivity of the herb field with that of the forest, by whatever criterion, clearly shows the field to be more resistant than the forest. The exposure reducing diversity to 50 percent in the first year was ~ 1000 R/day for the field and 160 R/day for the forest, a greater than fivefold difference in sensitivity (*3*).

The changes in these ecosystems under chronic irradiation are best summarized as changes in structure, although diversity, primary production, total respiration, and nutrient inventory are also involved. The changes are similar to the familiar ones along natural gradients of increasingly severe conditions, such as exposure on mountains, salt spray, and water availability. Along all these gradients the conspicuous change is a reduction of structure from forest toward communities dominated by certain shrubs, then, under more severe conditions, by certain herbs, and finally by low-growing plants, frequently mosses and lichens. Succession, insofar as it has played any role at all in the irradiated ecosystems, has simply reinforced this pattern, adding a very few hardy species and allowing expansion of the populations of more resistant indigenous species. The reasons for radiation's causing this pattern are still not clear (*3*, *6*), but the pattern is a common one, not peculiar to ionizing radiation, despite the novelty of radiation exposures as high as these.

Its commonness is illustrated by the response to fire, one of the oldest and most important disruptions of nature. The oak-pine forests such as those on Long Island have, throughout their extensive range in eastern North America, been subject in recent times to repeated burning. The changes in physiognomy of the vegetation follow the above pattern very closely—the forest is replaced by communities of shrubs, especially bear oak (*Quercus ilicifolia*), *Gaylussacia*, and *Vaccinium* species. This change is equivalent to that caused by chronic exposure to 40 R/day or more. Buell and Cantlon (*7*), working on similar vegetation in New Jersey, showed that a further increase in the frequency of fires resulted in a differential reduction in taller shrubs first, and a substantial increase in the abundance of *Carex pensylvanica*, the same sedge now dominating the sedge zone of the irradiated forest. The parallel is detailed; radiation and repeated fires both reduce the structure of the forest in similar ways, favoring low-growing hardy species.

The similarity of response appears to extend to other vegetations as well. G. L. Miller, working with F. McCormick at the Savannah River Laboratory, has shown recently that the most radiation-resistant and fire-resistant species of 20-year-old fields are annuals and perennials characteristic of disturbed places (*8*). An interesting sidelight of his study was the observation that the grass stage of long leaf pine (*Pinus palustris*), long considered a specific adaptation to the fires that maintain the southeastern savannahs, appears more resistant to radiation damage than the mature trees. At a total acute exposure of 2.1 kR (3 R/day), 85 percent of the grass-stage populations survived but only 55 percent of larger trees survived. Seasonal variation in sensitivity to radiation damage has been abundantly demonstrated (*9*), and it would not be surprising to find that this variation is related to the ecology of the species. Again it appears that the response to radiation is not unique.

The species surviving high radiation-exposure rates in the Brookhaven experiments are the ones commonly found in disturbed places, such as roadsides, gravel banks, and areas with nutrient-deficient or unstable soil. In the forest they include *Comptonia peregrina* (the sweet fern), a decumbent spiny *Rubus*, and the lichens, especially *Cladonia cristatella*. In the old field one of the most conspicuously resistant species was *Digitaria sanguinalis* (crabgrass) among several other weedy species. Clearly these species are generalists in the sense that they survive a wide range of conditions, including exposure to high intensities of ionizing radiation—hardly a common experience in nature but apparently one that elicits a common response.

With this background one might predict that a similar pattern of devastation would result from such pollutants as oxides of sulfur released from smelting. The evidence is fragmentary, but Gorham and Gordon (*10*) found around the smelters in Sudbury, Ontario, a striking reduction in the number of species of higher plants along a gradient of 62 kilometers (39 miles). In different samples the number of species ranged from 19 to 31 at the more distant sites and dropped abruptly at 6.4 kilometers. At 1.6 kilometers, one of two randomly placed plots (20 by 2 meters) included only one species. They classified the damage in five categories, from "Not obvious" through "Moderate" to "Very severe." The tree canopy had been reduced or eliminated within 4.8 to 6.4 kilometers of the smelter, with only occasional sprouts of trees, seedlings, and successional herbs and shrubs remaining; this damage is equivalent to that produced by exposure to 40 R/day. The most resistant trees were, almost predictably to a botanist, red maple (*Acer rubrum*) and red oak (*Quercus rubra*). Other species surviving in the zones of "Severe" and "Very severe" damage included *Sambucus pubens*, *Polygonum cilinode*, *Comptonia peregrina*, and *Epilobium angustifolium* (fire weed). The most sensitive plants appeared to be *Pinus strobus* and *Vaccinium myrtilloides*. The pine was reported no closer than 25.6 kilometers (16 miles), where it was chlorotic.

This example confirms the pattern

of the change—first a reduction of diversity of the forest by elimination of sensitive species; then elimination of the tree canopy and survival of resistant shrubs and herbs widely recognized as "seral" or successional species or "generalists."

The effects of herbicides, despite their hoped for specificity, fall into the same pattern, and it is no surprise that the extremely diverse forest canopies of Viet Nam when sprayed repeatedly with herbicides are replaced over large areas by dense stands of species of bamboo (*11*).

The mechanisms involved in producing this series of patterns in terrestrial ecosystems are not entirely clear. One mechanism that is almost certainly important is simply the ratio of gross production to respiration in different strata of the community. The size of trees has been shown to approach a limit set by the amount of surface area of stems and branches in proportion to the amount of leaf area (*12*). The apparent reason is that, as a tree expands in size, the fraction of its total surface devoted to bark, which makes a major contribution to the respiration, expands more rapidly than does the photosynthetic area. Any chronic disturbance has a high probability of damaging the capacity for photosynthesis without reducing appreciably the total amount of respiration; therefore, large plants are more vulnerable than species requiring less total respiration. Thus chronic disturbances of widely different types favor plants that are small in stature, and any disturbance that tends to increase the amount of respiration in proportion to photosynthesis will aggravate this shift.

The shift in the structure of terrestrial plant communities toward shrubs, herbs, or mosses and lichens, involves changes in addition to those of structure and diversity. Simplification of the plant community involves also a reduction of the total standing crop of organic matter and a corresponding reduction in the total inventory of nutrient elements held within the system, a change that may have important long-term implications for the potential of the site to support life. The extent of such losses has been demonstrated recently by Bormann and his colleagues in the Hubbard Brook Forest in New Hampshire (*13*), where all of the trees in a watershed were cut, the cut material was left to decay, and the losses of nutrients were monitored in the runoff. Total nitrogen losses in the first year were equivalent to twice the amount cycled in the system during a normal year. With the rise of nitrate ion in the runoff, concentrations of calcium, magnesium, sodium, and potassium ions rose severalfold, which caused eutrophication and even pollution of the streams fed by this watershed. The soil had little capacity to retain the nutrients that were locked in the biota once the higher plants had been killed. The total losses are not yet known, but early evidence indicates that they will be a high fraction of the nutrient inventory, which will cause a large reduction in the potential of the site for supporting living systems as complex as that destroyed—until nutrients accumulate again. Sources are limited; the principal source is erosion of primary minerals.

When the extent of the loss of nutrients that accompanies a reduction in the structure of a plant community is recognized, it is not surprising to find depauperate vegetation in places subject to chronic disturbances. Extensive sections of central Long Island, for example, support a depauperate oak-pine forest in which the bear oak, *Quercus ilicifolia*, is the principal woody species. The cation content of an extremely dense stand of this common community, which has a biomass equivalent to that of the more diverse late successional forest that was burned much less recently and less intensively, would be about 60 percent that of the richer stand, despite the equivalence of standing crop. This means that the species, especially the bear oak, contain, and presumably require, lower concentrations of cations. This is an especially good example because the bear oak community is a long-lasting one in the fire succession and marks the transition from a high shrub community to forest. It has analogies elsewhere, such as the heath balds of the Great Smoky Mountains and certain bamboo thickets in Southeast Asia.

The potential of a site for supporting life depends heavily on the pool of nutrients available through breakdown

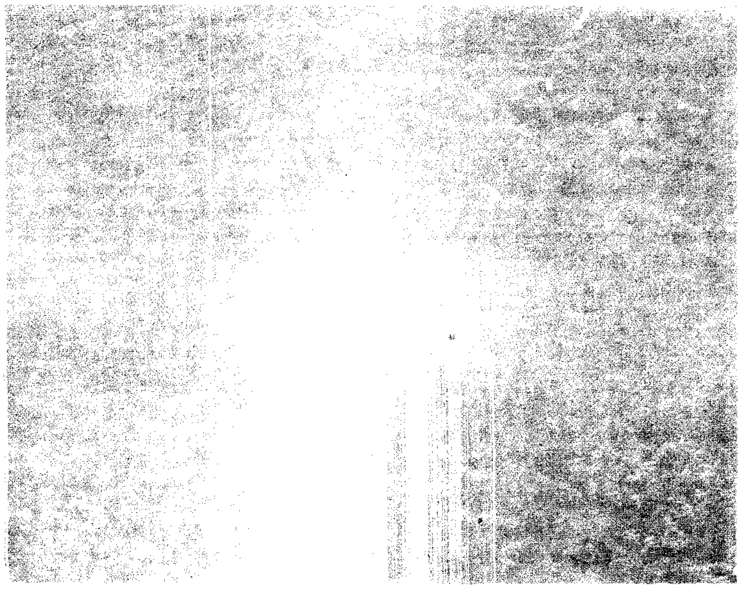

Fig. 1. The effects of chronic gamma radiation from a 9500-curie ^{137}Cs source on a Long Island oak-pine forest nearly 8 years after start of chronic irradiation. The pattern of change in the structure of the forest is similar to that observed along many other gradients, including gradients of moisture availability and of exposure to wind, salt spray, and pollutants such as sulfur dioxide. The five zones are explained in the text. The few successional species that have invaded the zones closest to the source appear most conspicuously as a ring at the inner edge of zone 2. These are species characteristic of disturbed areas such as the fire weed, *Erechtites hieracifolia*, and the sweet fern, *Comptonia peregrina*, among several others. [The successional changes over 7 years are shown by comparison with a similar photograph that appeared as a cover of *Science* (*16*)].

of primary minerals and through recycling in the living portion of the ecosystem. Reduction of the structure of the system drains these pools in whole or in part; it puts leaks in the system. Any chronic pollution that affects the structure of ecosystems, especially the plant community, starts leaks and reduces the potential of the site for recovery. Reduction of the structure of forests in Southeast Asia by herbicides has dumped the nutrient pools of these large statured and extremely diverse forests. The nutrients are carried to the streams, which turn green with the algae that the nutrients support. Tschirley (*11*), reporting his study of the effects of herbicides in Viet Nam, recorded "surprise" and "pleasure" that fishing had improved in treated areas. If the herbicides are not toxic to fish, there should be little surprise at improved catches of certain kinds of fish in heavily enriched waters adjacent to herbicide-treated forests. The bamboo thickets that replace the forests also reflect the drastically lowered potential of these sites to support living systems. The time it takes to reestablish a forest with the original diversity depends on the availability of nutrients, and is probably very long in most lateritic soils.

In generalizing about pollution, I have concentrated on some of the grossest changes in the plant communities of terrestrial ecosystems. The emphasis on plants is appropriate because plants dominate terrestrial ecosystems. But not all pollutants affect plants directly; some have their principal effects on heterotrophs. What changes in the structure of animal communities are caused by such broadly toxic materials as most pesticides?

The general pattern of loss of structure is quite similar, although the structure of the animal communities is more difficult to chart. The transfer of energy appears to be one good criterion of structure. Various studies suggest that 10 to 20 percent of the energy entering the plant community is transferred directly to the animal community through herbivores (*14*). Much of that energy, perhaps 50 percent or more, is used in respiration to support the herbivore population; some is transferred to the detritus food chain directly, and some, probably not more than 20 percent, is transferred to predators of the herbivores. In an evolutionarily and successionally mature community, this transfer of 10 to 20 percent per trophic level may occur two or three times to support carnivores, some highly specialized, such as certain eagles, hawks, and herons, others less specialized, such as gulls, ravens, rats, and people.

Changes in the plant community, such as its size, rate of energy fixation, and species, will affect the structure of the animal community as well. Introduction of a toxin specific for animals, such as a pesticide that is a generalized nerve toxin, will also topple the pyramid. Although the persistent pesticides are fat soluble and tend to accumulate in carnivores and reduce populations at the tops of food chains, they affect every trophic level, reducing reproductive capacity, almost certainly altering behavioral patterns, and disrupting the competitive relationships between species. Under these circumstances the highly specialized species, the obligate carnivores high in the trophic structure, are at a disadvantage because the food chain concentrates the toxin and, what is even more important, because the entire structure beneath them becomes unstable. Again the generalists or broad-niched species are favored, the gulls, rats, ravens, pigeons and, in a very narrow short-term sense, man. Thus, the pesticides favor the herbivores, the very organisms they were invented to control.

Biological evolution has divided the resources of any site among a large variety of users—species—which, taken together, confer on that site the properties of a closely integrated system capable of conserving a diversity of life. The system has structure; its populations exist with certain definable, quantitative relationships to one another; it fixes energy and releases it at a measurable rate; and it contains an inventory of nutrients that is accumulated and recirculated, not lost. The system is far from static; it is subject, on a time scale very long compared with a human lifespan, to a continuing augmentive change through evolution; on a shorter time scale, it is subject to succession toward a more stable state after any disturbance. The successional patterns are themselves a product of the evolution of life, providing for systematic recovery from any acute disturbance. Without a detailed discussion of the theory of ecology, one can say that biological evolution, following a pattern approximating that outlined above, has built the earth's ecosystems, and that these systems have been the dominant influence on the earth throughout the span of human existence. The structure of these systems is now being changed all over the world. We know enough about the structure and function of these systems to predict the broad outline of the effects of pollution on both land and water. We know that as far as our interests in the next decades are concerned, pollution operates on the time scale of succession, not of evolution, and we cannot look to evolution to cure this set of problems. The loss of structure involves a shift away from complex arrangements of specialized species toward the generalists; away from forest, toward hardy shrubs and herbs; away from those phytoplankton of the open ocean that Wurster (*15*) proved so very sensitive to DDT, toward those algae of the sewage plants that are unaffected by almost everything including DDT and most fish; away from diversity in birds, plants, and fish toward monotony; away from tight nutrient cycles toward very loose ones with terrestrial systems becoming depleted, and with aquatic systems becoming overloaded; away from stability toward instability especially with regard to sizes of populations of small, rapidly reproducing organisms such as insects and rodents that compete with man; away from a world that runs itself through a self-augmentive, slowly moving evolution, to one that requires constant tinkering to patch it up, a tinkering that is malignant in that each act of repair generates a need for further repairs to avert problems generated at compound interest.

This is the pattern, predictable in broad outline, aggravated by almost any pollutant. Once we recognize the pattern, we can begin to see the meaning of some of the changes occurring now in the earth's biota. We can see the demise of carnivorous birds and predict the demise of important fisheries. We can tell why, around industrial cities, hills that were once forested now are not; why each single species is important; and how the increase in the temperature of natural water bodies used to cool new reactors will, by augmenting respiration over photosynthesis, ultimately degrade the system and contribute to degradation of other interconnected ecosystems nearby. We can begin to speculate on where continued, exponential progress in this direction will lead: probably not to extinction—man will be around for a long time yet—but to a general degradation of the quality of life.

The solution? Fewer people, unpopular but increasing restrictions on technology (making it more and more expensive), and a concerted effort to tighten up human ecosystems to reduce their interactions with the rest of the earth on whose stability we all depend. This does not require foregoing nuclear energy; it requires that if we must dump heat, it should be dumped into civilization to enhance a respiration rate in a sewage plant or an agricultural ecosystem, not dumped outside of civilization to affect that fraction of the earth's biota that sustains the earth as we know it. The question of what fraction that might be remains as one of the great issues, still scarcely considered by the scientific community.

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RADIONUCLIDE CYCLING: CURRENT STATUS AND FUTURE NEEDS*

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(*Presented by* S. I. AUERBACH)

Abstract—By definition radionuclide cycling implies recurrent transfers of radioelements between and within ecosystems of the biosphere. The circulation of elements in ecosystems is an important regulatory process as well as a possible boundary condition for characterizing ecosystems. Because of increased recognition of the importance of cycling there has been a considerable increase in biogeochemical studies of terrestrial environments. That the ecologic processes of biogeochemical cycling govern the movement of and are the determinants affecting long-term behavior of long-lived radionuclides, were not recognized sufficiently to merit serious research attention until the late 1950's. Since then, radionuclide cycling has become a recognized facet of radioecological research. The concept currently appears to include four categories of investigation. They are: (1) deductive analyses derived from studies of fallout nuclides in different trophic levels of varying ecosystems, (2) tracer experiments to elucidate links in a food chain and develop data on rate of movement in the chain, (3) studies of rates of turnover of particular radionuclides within a single trophic level and (4) experiments employing tracers to measure the complete cycle in an ecosystem. Current problems such as interpretation of the significance of ^{90}Sr and ^{137}Cs levels in selected compartments of arctic ecosystems reinforce the need for more experiments of the fourth category emphasizing simple ecosystems.

RADIONUCLIDE cycling is an ecosystem process. To the ecologist, the problem of radionuclides in the environment and the understanding of their behavior is approached within an ecosystem framework. Uptake, bioaccumulation, discrimination, reduction factors, concentration factors, etc., represent specific and familiar facets of radionuclide cycling.

The classic paper of LINDEMANN(1) first clarified and defined the concept of trophic levels and tropho-dynamics. Many of the basic ideas underlying subsequent studies of food webs and food chains, derived from this paper. By the mid 1940's, a number of workers developed and clarified many general aspects of ecosystems which are now being studied in detail. Energetics, turnover, element circulation and productivity achieved recognition among ecologists as key processes in the dynamics of ecosystems during this period. These developments are related to names familiar to most, if not all of us. In the early 1950's the conceptual framework of modern ecosystem ecology was established. In the middle 1950's ecological research was undertaken in a significant and cohesive fashion within the Atomic Energy Commission. Environmental research, which had been principally the systematic documentation of levels of radionuclide contamination in various parts of the environment, began to shift to investigations of environmental contamination within an ecological context. After 10 years, it is appropriate to review these developements and hopefully to assess the needs and trends for the next 10 years.

The purpose of such investigations is still to provide radiation protection to man. Our criteria for radiation protection are still based on recommendations of the Federal Radiation Council which in turn derives much of its information from the recommendations of the National Council on Radiation Protection and the International Commission on Radiological

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Protection. The problems associated with the development of radiation protection standards, and their application are not explicitly part of this symposium. The equally important question of the interpretation of the significance of given levels of radioactivity in the environment, on the other hand, is very much related to this symposium because there are many ecological factors which must be considered before the significance of radioactivity in the environment can be interpreted within the framework of the recommendations of the radiation protection agencies. That this is so and is widely recognized, is one of the accomplishments of the past 10 years.

The recognition of causative factors represents only an early stage in the understanding process. Most practicing ecologists early recognized many of the aspects of the cycling problems as being special cases of an ecosystem process. Our responsibility, however, has been and will continue to be one of providing definition, especially quantitative definition of these factors and their precise role in the steps of transfer of radionuclides through ecosystems and ultimately to man.

This continuing responsibility does not obligate us to the exclusion of our other equally important task, which is the development of the basic understanding of the ecological factors involved. The opportunity, in fact the demand, for basic research and its rapid feedback to application has been unique in this area of ecology. Reinforcement of this relationship devolves upon all of us, and would seem to be the special province of those concerned with the area we are referring to as cycling of radionuclides.

By definition radionuclide cycling implies recurrent transfers of radioelements between and within ecosystems. This definition stems from the broader concept of materials transfer of element circulation in ecosystems, a process that is considered to regulate and to maintain ecosystems in a steady state within particular climatic and physiographic zones. "To demonstrate and interpret the relative importance of rates of internal circulation vs rate of import-export (as part of a larger-scale geochemical cycle) is one of the unifying problems of cycling studies" (OLSON(2)).

In a broad sense, biological interchanges or interactions represent the means by which elements are moved through the steps comprising a cycle. Consequently the entry of radioactive elements into an ecosystem or several ecosystems will, in time, lead to their distribution throughout the entire complex of organisms in the system. Specific activity is often used as a measure of radioisotopic contamination of organisms, or of their surroundings, while the ratio between these units is an expression of the enrichment factor or degree of contamination of the organisms relative to their environment.

The objectives of radionuclide cycling research are to clarify the steps in these processes, to analyze the stable as well as the radioelements, and to describe and quantify the biological trophic levels and their normal changes such as growth, life histories and production.

Thus radionuclide cycling is intimately associated with the problems of contamination of the different environments of the biosphere and with the underlying ecological processes. Radionuclide cycling research presently encompasses four categories of investigation. These are: (1) deductive analyses derived from studies of fallout nuclides in different trophic levels of various ecosystems (the category of greatest research efforts and interest), (2) tracer experiments to elucidate links in a food chain and to develop information on the rates of transfer in the chain, (3) studies on the rates of turnover of particular radionuclides within a single trophic level and (4) experiments employing tracers to elucidate and quantify the complete cycle in an ecosystem.

It might be useful to review briefly some recent stages of development of radionuclide cycling as illustrated in past key symposia. Four past meetings which represent key stages in the development were: the First and Second International Conferences on the Peaceful Uses of Atomic Energy in 1955 and 1958, the Conference on Radioisotopes in the Biosphere in 1960 and the First National Symposium on Radioecology in 1961.

In the 1955 Geneva conference, the relationship between ecological processes and problems of the nuclear age essentially was first presented to an international audience. Recognition that food chains are the avenues by which radionuclides become available for direct ingestion by man was explicit in the paper of CHAMBERLAIN, LOUTIT, MARTIN and RUSSELL.(3) They developed further the relationship between levels of contamination by aerial deposition and the criteria for intake. An important contribution was the derivation of maximum permissible levels for different fission products deposited on forage. ODUM(4) outlined and described some of the pertinent ecological factors bearing on the overall problems of radionuclide cycling. FOSTER and DAVIS,(5) pointed out several problems in aquatic cycling which still remain as complications in our studies. These were the problems of adsorption vs absorption, seasonal variation, and differences in trophic level accumulation. Valuable and new ecological data about biological monitoring near nuclear processing facilities were presented by HANSON and KORNBERG.(6) Problems of fission product accumulation in plants were highlighted by the paper of REDISKE and HUNGATE.(7) Biological cycling of fission products was introduced by YOSHIO HIYAMA(8) in his paper on contamination of marine organisms. He suggested that food chain transfers were governed not only by biological decay, which I would interpret as loss at each trophic level, but also by reduced absolute quantities consumed by each organism in the next higher trophic level.

By the time of the second International Conference (1958) evidence was ample that increased interest and considerable emphasis were being directed toward the problems of environmental contamination of terrestrial food chains. This evidence was manifest both in numbers of papers and in their scope.

The universal recognition of ^{90}Sr as perhaps the major problem isotope resulted in numerous papers on diverse aspects of the cycling of this radionuclide. SPITSYN *et al.*(9) reviewed the extensive work on migration of radioelements in soil. FREDRIKSSON *et al.*(10) presented comprehensive data on ^{90}Sr uptake by various agricultural crops under differing soil conditions. They demonstrated the importance both of crop yield on uptake of radionuclides and of calcium content of the soil in affecting ^{90}Sr uptake. In Sweden, and presumably elsewhere, an increase of calcium to a value equivalent to 50 per cent of the cation exchange capacity of soil had little effect on the uptake of strontium by plants. The generalization that minimum uptake of ^{90}Sr by agricultural crops would result from those practices normally used to ensure good crop production began to emerge at this conference. GULYAKIN and YUDINTSEVA,(11) in reviewing Russian studies on accumulation of fission products in wheat and peas, demonstrated that the concentration (per unit weight) of plant material of fission products decreased with increased growth during the growing season. Presumably factors which enhance crop production would result in reduced concentration in the vegetation though not necessarily in the overall crop burden. The Russian workers presented experimental data tending to show that various fertilizer combinations increased production and reduced radionuclide content.

Emphasis on fallout, its redistribution, as well as its entry into plants and animals characterized the work presented on terrestrial aspects of radionuclide behavior at this conference. Ecological studies of trophic level transfers, both theoretical and empirical, were a feature of the aquatic and marine reviews. These important concepts were especially dealt with in the papers of ATEN,(12) PENDLETON and HANSON(13) and DAVIS *et al.*(14)

A 1959 symposium on the ecology of radioisotopes was held at the University of Minnesota and dealt with information relating to the pathway of radioisotopes from the time they enter soils until they are excreted from living systems. Considerable emphasis was placed on the relation of fallout elements to agricultural soils and crop plants.

Here perhaps the most significant contribution was that of SCOTT RUSSELL(15) who demonstrated that dietary ^{90}Sr contamination was related to the rate of fallout or rainout deposition and not to the cumulative amount in the soil. RUSSELL's data on the importance of root mat or 'plant base' absorption showed that particular ecological factors must be considered in broad food chain evaluations. This factor was first ascertained as a result of ^{90}Sr measurements in hill pastures. Because of localized ecological factors such as shallow soil, there was present a dense mat of roots and organic matter not in association with the soil proper. Consequently ^{90}Sr and other radioelements deposited by rainfall would be entrapped in this zone and made available for immediate uptake by the plants. This finding graphically illustrated a situation of which many ecologists were implicitly aware. Namely the generalized predictions of fallout behavior based on broad standardized sampling techniques aimed particularly at obtaining information on special phases of the human food chain could be subject to wide variance because of local or regional ecological conditions.

At this conference NORMAN(16) carefully drew attention to some of the gaps existing in radionuclide cycling studies. His recommendation for an intensive study of the soils of a single small watershed in relation to ^{90}Sr and ^{137}Cs behavior, particularly to ascertain the extent of variation of concentration as a function of localized distribution was most timely. Such a study would still be useful today, especially if it included measurements which would enable the calculation of run off rates and transfer coefficients from land to water. Actually in 1959 such localized studies were already underway, although not within the context of a watershed. Part of the efforts of the late ROYAL SHANKS was to ascertain the variation in concentration of radionuclides in the upper soils of a local habitat. As SHANKS and DESELM(17) subsequently showed for ^{137}Cs distribution in White Oak Lake bed, the divergence from the mean can be considerable. Similar efforts for ^{90}Sr had long been underway at the Nevada Test Site by groups from UCLA.

The phenomenom of foliar absorption, which at times is emphasized to a point that implies it is a recent phenomenom, was put in proper perspective by BIDDULPH(18) and NORMAN.(19) It, like the leaching of inorganic and organic solutes from leaves was well established. However, within differing ecological communities or ecosystems, leaf area, surface characteristics and root biomass and distribution may have considerable impact on both the rates of transfer and the quantities of nuclide transferred between species or individuals in the system.

The First National Symposium on Radioecology provided ecologists concerned with atomic energy problems a chance to bring together the current information that was being developed within their own area of expertise. The salient developments were several in number.

First, the problems in understanding and interpreting the behavior of radioelements in natural environments are essentially the same as those concerned with the behavior of radioelements in simpler situations. If this is the case, then results of hypotheses derived from the former situations should have broader application. Second, movement of radionuclides through ecosystems is more than a matter of transfer between individuals or groups of individuals. The transfer must be related to the total mass of individuals which comprise a particular feeding level. The reason is that the quantity of protoplasm which can be produced and maintained at each trophic level of an ecosystem is relatively fixed. Consequently, any understanding and especially any prediction of the movement or cycling behavior of radionuclides must take into account this difference between individuals and the total biomass of a particular trophic level. The importance of this relationship between nuclide transfer and biological productivity was developed in the papers of DESELM and SHANKS(20) and OLSON.(21)

It is one matter to know that food chains are important. It is quite another matter to identify and perhaps quantify the complex chains in terrestrial ecosystems. Here the importance of using tracers cannot be overemphasized. ODUM and KUENZLER(22) demonstrated how radioactive tagging can aid in the isolation of "untangling" of food chains, as well as aid in the determination of the specific heterotrophic populations involved in the transfer process.

The equilibrium quantity of radionuclide in each trophic level above that of the photosynthetic producer is defined as the difference between the rate of ingestion and the rate of loss. The problem at the trophic level is more complex because the rate of turnover, which is a function of the biological half-life of the radionuclide, is related to species physiology. The elimination of an isotope may be a single exponential process or a multiple one, with each phase having a distinctive rate which is related to the particular compartment size within the individual. The problem of determining equilibrium levels in all trophic levels of an ecosystem is therefore, a challenging one, easily recognized, but difficult to execute under field conditions. CROSSLEY(23) and KAYE and DUNAWAY(24) illustrated some of the difficulties as well as the implications of the use of this information. In insect food chain studies on White Oak Lake bed broad differences in equilibrium levels between ^{90}Sr and ^{137}Cs in insect trophic levels were related to the species turnover times for these isotopes. Since these two isotopes are metabolized quite differently by insects, gross field sampling techniques sufficed to bring out the differences in food chain behavior, whereas as illustrated later in this symposium the delineation of the rates of turnover of a single isotope in a complex food web is much more difficult. KAYE and DUNAWAY(24) attempted to derive equilibrium levels of radionuclide burdens in cotton rats living on White Oak bed, using known body burdens obtained from sampling individuals of the field population and using literature data on feeding and elimination rates for other species of rodents. The wide divergencies found between actual body burdens and calculated ones for the different isotopes examined illustrate the need for experimental determination of these parameters before applying interpretations to a field situation.

Mathematical modeling was outlined in the paper of OLSON(21) who illustrated techniques using an analog computer for quantifying rates of transfer of radionuclides between major compartments of an ecosystem. Such models can lead to the prediction of the extent of movement of nuclides and the time relations thereof. However, rigorous testing of mathematical models will require more elaborate tracer experiments on a larger scale than has heretofore been undertaken.

Since the first radioecology symposium two major situations have developed which have had apparently conflicting effects on the future of radionuclide cycling research. First is the test ban treaty which, together with the impressive information available on fallout behavior and its consequences, has tended to focus attention away from any possible need to look intensively into various ecological "byways" of movement. The second situation concerns the problems in arctic ecosystems. Details of this ecosystem will be treated in subsequent papers and only some salient aspects will be considered here.

Because of a unique interplay of ecological factors, natives in arctic ecosystems appear to be accumulating larger body burdens of ^{90}Sr and ^{137}Cs than individuals of populations elsewhere. This situation has evoked considerable concern among the people and public officials of these regions. In view of the seeming quietitude induced by the test ban treaty it is important to recognize that a latent concern, of indeterminate dimensions, exists in the public over the problems associated with radioactivity in the environment. The ecological factors which are involved in arctic ecosystems concern the food chain and human components. In the tundra ecosystems, because of a number of climatic and biological factors, higher quantities of fallout radionuclides tend to accumulate in the producer levels such as lichens, mosses and sedges. The higher trophic levels based on these producers, especially large herbivores such as caribou (reindeer) have greater body burdens of long-lived radionuclides. Since caribou are an important item in the human diet of these regions, as are other native animals, concern has been and is being expressed over the possibility that the native populations are developing body burdens of long-lived radionuclides in excess of the burdens in populations living in temperate or other regions. Concern is likewise expressed over the applicability of our radiation standards to these populations when these standards have been developed for populations of vastly different habits. As an example, in the terms of a possible long term genetic dose, *are* the present MPC values which are applied to large populations, equally applicable to limited populations such as the Lapps and Eskimos (both less than 40,000) which consist of isolated groups where consanguineous marriages may not be uncommon? In such isolated groups, the limited gene pools increase the possibility of unfavorable homozygous recessive traits. It appears to me however, before we settle on some long term conclusions about the impact of radioactivity on these human populations that a number of the aspects of the food chain problem need to be clarified. We need data based on adequate samples on the rates of transfer of ^{90}Sr and ^{137}Cs for the different trophic levels. Information on equilibrium levels and on the steady state versus non-steady state transfer of ^{137}Cs would permit a more valid interpretation of the significance of the epidemiological findings on human dietary consumption and composition. Such interesting postulations as the resent hypothesis of PENDLETON *et al.*,(25) suggesting a regular threefold trophic level increase in ^{137}Cs need verification because of obvious importance to the Arctic ecosystem situation as well as for other areas.

Earlier I pointed out that radionuclide cycling encompasses fallout analyses of various ecological situations, tracer experiments to untangel food webs, trophic level turnover studies, and ecosystem experiments employing tracers. It appears that at present there is still a disproportionately large effort going into the first category. Will the efforts that go into measuring smaller quantities of radionuclides with more sophisticated equipment, collecting more samples for laborious separation and analysis, and applying refined data processing—will all this provide more than appropriate deductions for each land region of interest? The data derived from such studies are important and valuable for providing guidelines as well as information on specific levels that may be anticipated. Nevertheless, such information seems to be less able to stand the test of rigorous inquiry by the general and scientific public than do data obtained under conditions of more precise control. Perhaps the time is at hand when we can seriously consider undertaking more extensive experiments on rates of turnover by key organisms in key trophic levels or long term experiments to quantify the steps in a radionuclide cycle in a particular ecosystem. The technology is both adequate and available, the mathematical tools are at hand and the general problem is certainly well defined. The relatively small but important efforts that will be reported at this symposium are in many ways still pilot scale studies of the type of experiments and investigations that need to be undertaken.

Although weapons testing has ceased, two long-term concerns related to environmental contamination by radionuclides remain. These are the possible threat of widespread contamination from the use of nuclear weapons and the widespread use of nuclear power and attendent waste processing which may pose localized problems of contamination. Let us also not forget that radionuclide cycling research has application to another of our major concerns—the pollution of our environments by chemicals.

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RADIATION AND ANIMAL POPULATIONS: PROBLEMS, PROGRESS AND PROJECTIONS*

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(*Presented by* N. R. French)

Abstract—A review of recent literature indicates much progress since the 1961 Radioecology Symposium, and suggests the importance of measuring the functional efficiency of irradiated populations. Population ecology provides methods suitable for evaluating the performance of populations. Dosimetry in radiation studies is simplified by new microthermoluminescent dosimeters. A population can be irradiated by administration of a single acute exposure of each individual animal, by chronic exposure of a large study area with an established population, or by administration of an isotope for internal exposure of the animals. Irradiation may impair a population primarily through reduction in fertility, and to some extent by reduction of life-span. In mammalian populations, reduced fertility would not under ordinary conditions be hazardous to survival, except when other environmental stress causes a shift in the age structure of the population to the point where reproduction by older individuals is important to maintenance of the population.

INTRODUCTION

The purpose of this paper is to review some of the important literature on this subject that has appeared since the first symposium on Radioecology held in 1961 at Colorado State University, to mention some of the important work that is under way and is not specifically discussed in the papers to follow, to mention certain areas of investigation which I believe need greater emphasis, and to present some opinions about the effects of radiation on animal populations.

IMPORTANT WORKS OF GENERAL INTEREST

Valuable bibliographies on terrestrial and fresh water radioecology compiled by Klement and Schultz(1–3) have been published by the U.S. Atomic Energy Commission. The first appeared in March 1962, and two supplements have appeared at yearly intervals. These are such convenient references that it is hoped the supplements will continue to appear.

An important article of general interest is the population study of the parasite, *Schistosoma japonicum*, the oriental blood fluke, by Hairston.(4) It is an exemplary analysis of a complex life-cycle, indicating the relative importance of the different hosts and of the various stages in the life-cycle to perpetuation of the species. It is a problem of both practical and theoretical importance, because at some critical combination of densities the maximum reproductive powers of the parasite can no longer overcome the lowered chances of success of the intermediate stages, suggesting a means of control.

RADIATION EFFECTS ON INVERTEBRATES

Some very important progress has been made in studying radiation effects on insect populations. Investigations by Erdman(5) of X-radiation effects on single species populations and mixed species populations of *Tribolium confusum* and *Tribolium castaneum* have indicated differences between two species in response to exposures between 2000 and 6000 R. Impaired

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reproductive ability was more serious in *Tribolium confusum*, and in mixed species populations it was the one eliminated.

Effects of gamma radiation on a population of *Drosophila melanogaster* may be inferred from laboratory studies of this species.(6) Irradiation of both sexes in various stages with exposures between 4 and 16 kR either reduced numbers of eggs or decreased the number hatching, and reduced life-span. Other insects, such as the European corn borer, show reduction of egg viability after exposure to 2500 R.(7)

That insect populations may respond more to radiation-induced changes in other organisms than to direct effects of radiation on the insects was indicated by the expansion of certain insect populations in the irradiated forest ecosystem at Brookhaven.(8)

The reproductive capability of a hermaphroditic snail was greatly reduced by radiation exposures between 4 and 9 kR.(9) Radiation sensitivity varied with age, and degree of damage and recovery time depended on dose. Fertility of offspring of irradiated animals was also affected, but less than in the treated generation.

RADIATION EFFECTS ON VERTEBRATES

The manifestations of radiation injury most important to animal populations are those affecting life-span and fertility. Life-span may be shortened 10 per cent or more in laboratory rodents if the radiation dose is more than half the $LD_{50/30}$ dose for the species.(10) Fertility is more greatly affected, as the reproductive cells are the most radiosensitive cells of the body. Two extremely valuable publications have recently appeared, both resulting from symposia. One deals with the effects of radiation on the reproductive system,(11) the other with the hereditary fitness of mammalian populations.(12)

After acute exposure of a few hundred roentgens, male mice remain fertile for a period of time, and then have a temporary period of sterility.(13) Fertility is eventually restored. Females subjected to smaller doses of ionizing radiation are fertile for a brief period and then become permanently sterile. The sex difference in response to radiation is due to the different array of germ cells present. The ovary contains essentially only primary oocytes, while in the male are found all the gametogenic stages from spermatogonia to mature sperm. Regeneration of the seminiferous epithelium from surviving spermatogonia can occur, but the ovary lacks a comparable stem cell, and the oocytes cannot be replaced once they are destroyed. The rate of development of reproductive cells, and the stage at which radiation occurs, is believed to account for observed differences in radiosensitivity between species.

Production of young by the male mouse is reduced after a dose of about 400 R at an early age.(14) In contrast, the young female is sterile after a dose of 100 R. Even a dose of 30 R to the young female results in greater reduction in the number of offspring produced than the dose of 400 R to the male.

As an aid in extrapolation from the results of the laboratory mouse to other species, it has been stated that the general radiation response of the seminiferous epithelium of the mouse is typical for all species.(13) This belief is based on the similarity of spermatogenesis and the similarity of fertility pattern of all irradiated males. The hypothesis has been supported by work with such diverse organisms as the grasshopper, *Drosophila*, silkworm and guinea pig. Species differences in response to radiation are greater in females, however. This may be due to different rates of development of the ova, and particularly the stage at which development is arrested. Since different stages of cell maturation show varying sensitivity to damage by ionizing radiation, the stage at which the oocytes remain until follicle maturation has considerable influence on the resulting fertility.

Chronic exposure of female albino rats at rates of 2, 5, 10 and 20 R/day showed an effect only on the fifth and sixth litters of those receiving 20 R/day.(15) There was no significant effect on litter sizes and total number of offspring in those receiving 2, 5 or 10 R daily through four successive litters.(16) Male albino rats became sterile at all exposures greater than 2 R/day, indicating the male is the more sensitive sex in this species.

Chronic exposure of albino mice to doses greater than 3 R/day results in sterility.(17) At dose rates up to 2.6 R/day the population has been continued more than ten generations, by selecting offspring from the first litters. In another experiment(18) albino mice exposed to 1 R of gamma radiation nightly were maintained through twenty-five generations. They then showed only reduction in size of the third and later litters, with earlier onset of sterility.

The excellent experimental design used by TOUCHBERRY(19) revealed rather precisely the cost, in terms of decreased number of offspring, to hybrid and inbred strains of albino mice from acute exposure to radiation. The decrease in number per litter in hybrids was 0.009 mice per roentgen given the male parent, and 0.027 mice per roentgen given the female parent. The decrease in number per litter for inbred animals was slightly less for males and slightly greater for females. The decrease in number resulting from irradiated males is attributed to dominant lethal mutations, while the decrease due to irradiation of females is due to both dominant lethal mutations and to somatic effects on the female parent.

Wild species of rodents appear to be much more resistant to damage from ionizing radiation, at least in terms of the LD_{50} dose.(20) It is not known if the reproductive system of these species is correspondingly resistant.

In reviewing the results of laboratory experiments on the effects of radiation on mammals, one is impressed with the remarkable variation in tolerance of the animals and persistence of the breeding lines. What seems to be required is methods of measuring the functional efficiency of the irradiated lines of animals. Some investigators have already turned to this, and have designed experiments demonstrating that the progeny from irradiated lines have altered protein metabolism or are more susceptible to stress in the form of cold or chronic gamma irradiation.(21) In all other respects the animals perform normally. What better test is there of the functional performance of organisms than their efficiency in utilizing the environmental resources of the habitat to which they are adapted? The variations in environmental factors which influence the organism, and the pressures of intra- and interspecific competition for space and other resources test every ability and adaptation of the organism to survive and persist. This is where ecology can make a valuable and much-needed contribution to understanding the total effects from irradiation. Continuation of the population through time is the ultimate test of the entire integrated damage to all individuals composing the population.

A more precise method of measuring the performance of individual animals in nature would, of course, be desirable. Laboratory methods of estimating energy expenditure by measurement of oxygen consumption or measurement of energy utilization by carbon dioxide production are indicators of physiological performance. Extrapolations from laboratory measurements to field populations are crude estimates at best. One method has been developed(22) which is suited for estimation of total carbon dioxide production over a limited period of time by a free-living animal. The body water of an animal is labeled with stable isotopes, and isotopic analysis of a small sample of blood at the beginning and the end of the time period is performed. The turnover rate of oxygen from the body water is greater than the turnover rate of the hydrogen. Hydrogen is lost as water, while oxygen is lost both as water and as CO_2. When the body water is labeled with $D_2{}^{18}O$, the difference between the two turnover rates can be measured, and the amount of oxygen lost as CO_2 can be calculated. To date, only one application of this method in the field has been performed, and that was to measure the energy requirements of pigeons in flight.(23) Isotopic analyses of the samples of body water have so far been performed only in the laboratory where the procedure was developed. Exacting techniques and procedures are required.

DOSIMETRY

Dosimetry in ecological studies involving radiation is often complicated by effects of shielding from structures or other organisms in the environment, and by mobility of the animals. Methods are now available for rather precise measurement of total exposure and absorbed dose even for fairly small organisms exposed to radiation. KAYE(24) has discussed in detail the utilization of small (1 × 6 mm) silver-activated metaphosphate glass rods, very useful for measuring exposure of plants and animals or absorbed tissue dose. Considerable caution is required in their use. Due to energy dependence, the characteristics of the radiation to which they are exposed must be known if the readings from the glass rods are to be correctly interpreted. Other factors such as mechanical alteration can affect the rods and cause spurious readings.

An improved dosimeter that is less subject to erroneous interpretation is the thermoluminescent dosimeter.(25) This utilizes a crystalline solid in which electrons freed during irradiation become trapped at lattice imperfections, and upon heating are released and recombine with the emission of light. Quantitative measurement of the light emitted permits determination of radiation exposure. Of several solids used in thermoluminescence studies, lithium fluoride is most acceptable for general use. The main advantage of lithium fluoride is its nearly flat response over a wide range of gamma ray energies.

Microthermoluminescent dosimeters, containing 0.6 mg of lithium fluoride sealed in glass capsules measuring 0.8 × 6.0 mm, have been developed for use in the ecological studies conducted by UCLA in Rock Valley at the Nevada Test Site.(26) An International Conference on Luminescence Dosimetry is being held in June 1965 at Stanford University, and includes many papers describing microthermoluminescent dosimeters. There is considerable interest in these devices and we can look forward to their increased utilization and availability.

PROBLEMS IN THE STUDY OF ANIMAL POPULATIONS

When dealing with a population we are necessarily concerned with numbers of animals. We have a sample of the gene pool of the geneticist. Hetergeneity characterizes the unit of our study. Two sample populations taken from the same gene pool may by chance behave in quite different ways. To compare two populations, the birth rate, death rate and age structure are principal manifestations of this level of organization and may be evaluated to estimate the potential for increase.

One major difficulty in the study of effects of radiation on animal populations is administration of a uniform radiation dose to the members of the population. It is as important to know the quantitative exposure ofthe population as to know the effects of the radiation exposure.

There are at least three techniques by which a population of animals can be exposed to radiation. Each individual can be temporarily removed from the population, given a single exposure to X-radiation or gamma radiation in the laboratory, and returned to the population. This method was used in investigations of *Peromyscus* populations by BLAIR (27–29) and by McCARLEY.(30) Probably the chief objection to this method from the standpoint of determining the population consequences of the radiation dose, is that the physiological condition of individual animals may not be the same at the time of irradiation, and therefore individual response may vary. For instance, if reproduction is seasonal, and irradiation of individuals is accomplished over many weeks or months, then the dose to one individual may profoundly influence breeding performance while exposure may have little effect on the reproduction of another.

A chronic radiation exposure to the population avoids the difficulties of the former method by exposing all animals at all stages of physiological activity and reproductive development. If all members of the population are to receive approximately the same exposure, however, the dose rate must be uniform. Such a study is under development at Oak Ridge National Laboratory, where they are using the ingenious method of adding radioactive cesium to the soil. If this is spread uniformly, an animal moving about on the surface of the ground will be subjected to the same dose rate in any portion of the study area. At the Nevada Test Site, we employed a different method to irradiate a desert community.(26) A single high level radioactive source is placed 15 m above the ground in the center of a circular study area, and a disc-shaped shield of lead under the source reduces the dose rate at ground level near the center of the circle. The lead near the edge of the disc is thinner than that of the central portion, and thus provides less shielding between the source and the ground as distance from the center of the circle increases. Although the dose rate is not uniform throughout the study area, the design has sufficiently reduced the variability to permit study of effects of the exposure on the rodent and reptile populations, as well as the plants. This system has the advantage of permitting removal of the radiation source by lowering it into a shielded container when personnel must work in the study area.

It seems possible to administer chronic exposure to a population by utilizing internal emitters. In the case of small mammals, contaminated food could be provided at regular intervals. The duration of the time interval must be determined by the effective half-life of the isotope in use. Under these conditions, the animal would have the maximum body burden of isotope, and hence the greatest radiation exposure, just after consumption of the contaminated food. After a single ingestion of contaminated food, the dose rate would begin to decline immediately, according to the effective half-life of the isotope. SIKOV and NOONAN[31] estimated the radiation dose received by internal organs of rats from ^{32}P, and determined the $LD_{50/30}$ for this type of administration. Dose distribution among internal organs varied with age of the animal. Bone marrow received the highest radiation dose. Use of other isotopes would give a different dose distribution. A disadvantage of the method for field studies is the variation in food consumption by individuals and consequent non-uniformity of dose. An advantage of the method, when isotopes of short half-life are utilized, is that time can be allowed for decay of radioactive material to safe levels before personnel enter the area for sampling or study of the population.

The second major difficulty in the study of irradiated animal populations is evaluation of effects. One of the characteristic features of radiation injury is that biological damage may be expressed a long time after a single exposure, or after many months of chronic exposure. Such damage may reduce the average life-span in the population. While life-span in laboratory animals can be evaluated by observing and recording the deaths of individuals, in nature the deceased animal is seldom observed. If individuals are under observation, or periodic census, then the disappearance of an animal must be interpreted as resulting from death or emigration. At the Nevada Test Site, our solution to this was to fence the study area to prevent migration.[26] A monthly census by live-trapping is made of the rodents in each 20-acre study area, and individual animals are marked for recognition. Under these conditions, when an individual ceases to appear in our trapping, it is assumed to be dead. There is little chance of escape from the study areas. Without the aid of a fence, the life-span in the population can be evaluated if the ages of individual animals can be determined. Unfortunately, it is difficult to estimate age in most wild species, and usually requires sacrifice of the animal. However, if the numbers of animals in different age groups can be determined, and the change in numbers of each age group over a period of time can be obtained, then the mortality of that age group over the time period is available. Add to this the mortality of different age groups and many time intervals, and you have the average mortality of the population throughout all age classes.

The reproductive system is the system most sensitive to damage by ionizing radiation. A natural population must have adequate fertility to offset the results of mortality, if the population is to maintain itself. This is particularly important when reproduction is of seasonal occurrence. During the short reproductive season a population must overcome the results of mortality, which continues through the entire year. In all successful species fertility is adequate to carry the population through the most adverse years encountered by the population. How much reserve capacity remains over and above this is generally unknown. How much radiation induced reduction of fertility can be tolerated by a population, and still enable it to recover from adverse environmental circumstances, is an open question.

Fertility of a natural population can only be estimated. The signs of fertility can be examined in sample animals removed from the population and sacrificed, but these are subject to error and lead only to estimates. Such signs are the number of embryos, number of placental scars in the uterus and number of corpora lutea in the ovaries. These are not always easily observed, and results must be interpreted with caution. Failure to account for intrauterine mortality at various stages of development can lead to erroneous results. In a confined population where animals are examined by live-trapping, fertility of the population can be estimated by the number of juvenile members added to the population during the reproductive season. This method will inevitably underestimate population fertility because of failure to account for mortality of the very young.

I have attempted to point out the most obvious difficulties and sources of error encountered in studies of natural populations. The potential importance of and critical need for results based upon the best methods we have for evaluating the consequences of ionizing radiation to natural populations of organisms make it imperative that such studies be conducted.

RADIATION AND POPULATION INCREASE

The increase or decrease of a population is governed by the difference between mortality and fertility. Mortality rate, or the probability of dying, varies with the age of individuals. Fertility, or production of young, also varies with age. Therefore, the age structure of the population has a great influence on the capacity of the population for increase.

The effect of radiation on r, the intrinsic rate of increase of a population, has been clearly shown by MARSHALL(32) in his work with *Daphnia pulex*. Chronic exposure to gamma radiation brought about a decrease in fertility and also a decrease in the average life-span of members of the population. The reduction in r was primarily effected by reduced fertility. The value of r became zero at a dose rate which, when administered through the lifetime of an organism, resulted in a total accumulated dose which was much less than the LD_{50} dose for these organisms when given as an acute exposure. Any increase in exposure reduced r even more, indicating a declining population doomed to extinction if conditions remain unchanged. With increased radiation exposure there was a change in the age structure of the population.

The intrinsic rate of increase, r, is a most useful statistic incorporating these varying attributes of the population. Mathematically, it is part of the exponent in the equation for exponential increase:

$$N_t = N_0e^{rt}$$

where N is the size of the population at time 0 and at time t, and e is the base of natural logarithms. If $r = 0$, the population is remaining stationary in time. If r is greater than 0, the population is increasing. If r is negative, the population is decreasing.

Another useful statistic is R_0, the multiplication per generation. It is related to r, the rate of increase, in the following manner:

$$R_0 = e^{rT}$$

where T is the mean generation time, or the average time between birth and reproduction. When $R_0 = 1$, the population is stationary, and each adult of the present generation is replaced by one adult in the next generation.

The three values, r, R_0 and T, are related to each other in such a way that any two of the values determine the third.(33) Small organisms have high values of r and short generation times. There is a generalized inverse relation between r and body size. Because of these relationships, r has been considered as a measure of the expected harshness of the environment in which the animals live. It would seem, therefore, to lend itself to evaluation of radiation effects on the population. The following changes in the population would tend to decrease r: an increase of age to first reproduction, a decrease in litter size, or a decrease in longevity.(34)

Now let us consider what might happen to a population that is exposed to some sublethal quantity of radiation. For this hypothetical example, I have utilized the data for albino rats presented by LESLIE, VENABLES and VENABLES(35) and for radiation effects the data of BROWN *et al.*(15) In a laboratory population the mortality curve (Fig. 1) indicates that during the reproductive life-span the most important mortality occurs among the very first weeks of life. Those that survive to become young adults have a much greater probability of living through the reproductive period than do the new-born animals. For those animals that attain sexual maturity, fertility increases rapidly to a maximum at about 5 or 6 months of age. After this age the decline in fertility is rapid at first, and then less rapid but still declining until they become nonreproductive. Animals greater than 20 months of age may continue to reproduce but, for purposes of discussion, they are

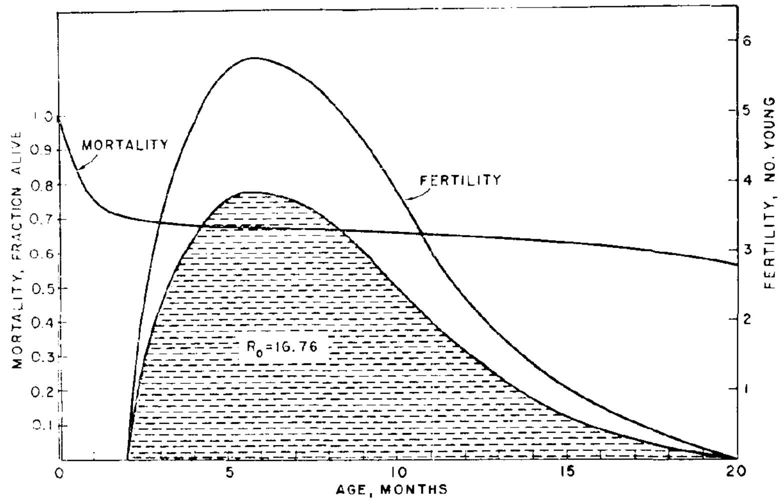

FIG. 1. Mortality, age specific fertility, and multiplication rate of the laboratory rat (from data in Ref. 35).

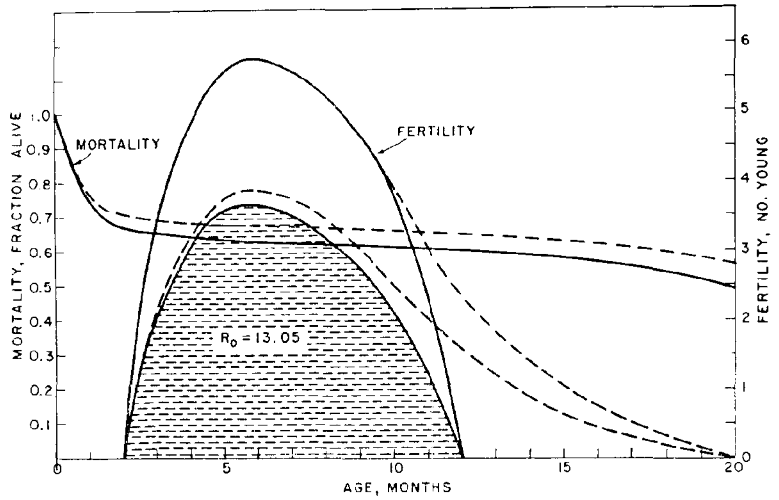

FIG. 2. Effect of radiation on mortality, age specific fertility and multiplication rate of the laboratory rat (data from Ref. 15).

here considered unimportant from the standpoint of population productivity.

When the two curves representing mortality and fertility are integrated, the result combines the expected survival with the expected rate of reproduction at each age interval. The area under the curve represents the average number of offspring produced per animal alive at the beginning of our time period, or the multiplication of the population per generation. In this case $R_0 = 16.76$.

When this particular rat population is subjected to radiation, there is a reduction in life-span of about 10 per cent (Fig. 2). The reduction in fertility as indicated in the figure is a result of females having four normal litters, the fifth litter reduced to one offspring, and none thereafter. Such fertility was reported by BROWN in female rats exposed to 20 R/day. The result is $R_0 = 13.05$, a reduction of about 22 per cent in the multiplication rate of the population. Note that the main reduction occurs in the tail of the curve. Instead of a negatively skewed curve, it is now nearly symmetrical. There is some reduction in the height of the curve, and this results from the reduction in average life-span which affects the period during which litter size remains normal.

The importance of the reduction in R_0 to a population will depend upon the severity of environmental conditions to which the population is subjected. The early litters, that is, the offspring of young females, contribute most to the rapid increase of an expanding population, or a population in a laboratory environment where it is free from the effects of density. For such a population to maintain itself, it is the early litters that are most important. The shortened span of reproduction from irradiation could be unimportant to such a population. From this standpoint it is fortunate that the reduction affects the later litters in the lifetime of a female.

If a population can get along well enough with a symmetrical R_0 curve, it may be questioned why there is a tail on the curve at all. Most animals for which data have been published show a positively skewed R_0 curve. COLE(34) has shown that offspring of the youngest females contribute nearly all the power behind the rate of increase. Early reproduction is highly advantageous from the standpoint of evolution and hence a positively skewed R_0 curve is likely to result from selection. The question as to why the tail should remain has been raised by LAUGHLIN.(36) He reasoned that older females have other selective advantages, such as increased power of survival, which could help a population through "a particularly nasty catastrophe". Reproduction by older females is therefore important in slowing the rate of decrease in unfavorable times.

If radiation were to reduce or destroy the capacity of older individuals of the population to reproduce, a population that experienced severe mortality among the younger members would be in jeopardy. This could happen if unusually severe conditions occurred during or shortly after the breeding season. Mortality curves of most animals, even of laboratory animals, show the greatest mortality rate among the very young. The desert rodent population which I have been studying since 1960 in southern Nevada was in such a precarious position last year. The rodents annually attained high numbers during the spring and early summer of almost twenty per acre, until the spring of 1963 when practically no young animals were added to the population. This appeared to be correlated with poor growing conditions generally, which in turn appeared to be correlated with unusually low winter rainfall. Mortality continued to reduce the population, and by the spring of 1964 their numbers were unusually low, perhaps only 10 per cent of the highest numbers in former years. But more important, the population consisted entirely of older individuals. Had these animals been subjected to a lifetime of low level radiation, it is possible they would have been faced with near extermination. It would appear that only during the most unfavorable years will we be able to determine the threshold for significant radiation damage to the natural population. Irradiation of our study area did not begin until February 1964, however, so we are only now beginning to examine the reproductive performance of animals exposed for a significant period of time. There was some reproduction during 1964, but our population remains low in numbers.

THE RATS OF ENGEBI

There remains unsolved the question of the remarkable survival and persistence of the Polynesian rats on Engebi Island in the Pacific.(37) Subjected to nuclear detonations four different times, during which the island received radiation exposures up to thousands of roentgens, and following which resident animal populations must have received excessive exposures from internal emitters for prolonged periods, *Rattus exulans* has survived and repopulated in spite of obvious mortality and undoubted genetic effects. This is spectacular even for a species known to be adaptable and successful.

Engebi is a 250-acre island in Eniwetok Atoll. It was used for early detonations in 1948 and 1951. It was 3 miles from the detonation in 1952, after which live rats could only be found at least 9 miles from the site of the explosion, and these were weak and ill. Another device, at the same distance from Engebi, was set off in 1954. After the last detonation, personnel of the University of Washington Laboratory of Radiation Biology estimated that rats in burrows had received at least 55–80 R exposure. After the 1952 explosions they estimated that any animal above ground would have received an exposure 2800–6700 R. Such a dose would be lethal to any known rodent. During the first 9 days after the shot, rats in burrows would have received between 250 and 2500 R. Still, an estimate by LOWMAN in 1955 indicated between 1000 and 4000 rats were active above ground during any daylight hour, and the total population was believed to be several times larger. It is possible that there were 10,000 rats inhabiting the island 1 y after the last contamination and 3 y after the devastating event that left wounded animals at distances three times as far as Engebi. The investigators ruled out repopulation from other islands and concluded that some nucleus of a population must have remained on the island to permit reappearance.

It is interesting to consider the possible growth of the *Rattus exulans* populations after the decimating events described. Much information on this and other species of rats in the Pacific has since been assembled in the publication *Pacific Island Rat Ecology* by TRACY I. STORER and associates.(38) One conclusion presented is that each female bears four additional females per year. This is an annual rate of multiplication, $R_a = 4$. Another estimate provided is that females have a mean reproductive life-span of 1.15 y, during which forty-one female offspring are produced per female, and 76 per cent of these die before puberty. This leaves ten survivors, or $R_a = 9$. The difference between the two estimates may result from separate investigations of stable populations and expanding populations. As to mortality, they present data indicating that the survival rate of young animals is 0.83 per month, that half of the original cohort of young animals is lost in 6.3 months, that adults have an annual probability of appearance of 0.4, and that few rats live to be 30 months old. Using these points, a curve can be constructed (Fig. 3) that may be considered as an approximation of the mortality curve for this species. The average litter size is given as 2.5, half of which may be considered females. Using the mortality curve and, in the absence of more accurate data on age specific fertility, assuming all litters are the same size, a table representing the age schedule of births and deaths has been constructed (Table 1). This provides an estimate of the multiplication per generation, $R_0 = 2.9$. This indicates that the population multiplies almost three times in the mean generation time of approximately 10 months, and is very close to the separate estimate of an annual multiplication rate of 4.

Table 1. Rattus exulans, *age schedule of births and deaths*
(from data in *Pacific Island Rat Ecology*)

x (months)	l_x	m_x	$l_x m_x$
0	1.00	0	0
3	0.57	1.25	0.71
6	0.39	1.25	0.49
9	0.30	1.25	0.38
12	0.25	1.25	0.31
15	0.22	1.25	0.28
18	0.19	1.25	0.24
21	0.16	1.25	0.20
24	0.12	1.25	0.15
27	0.09	1.25	0.11
30	0.03	1.25	0.04
			$R_0 = 2.91$

$$T = \frac{\Sigma l_x m_x x}{\Sigma l_x m_x} = \frac{29.70}{2.91} = 10.2$$

$$r = \frac{\ln R_0}{T} = \frac{1.06815}{10.2} = 0.10472$$

Consider what annual rate of multiplication, R_a, by the rat population is necessary to produce 10,000 individuals on Engebi in 3 years (Fig. 4). If $R_a = 4$, a population of 156 animals in 1952 could have produced the 1955 population of 10,000. On Engebi, however, radiation certainly reduced fertility of the species. It is difficult to make a quantitative estimate of the

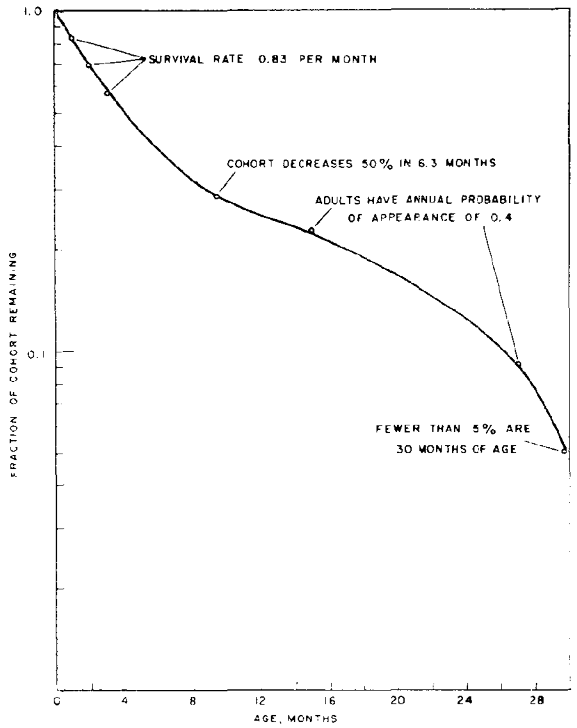

FIG. 3. Mortality curve for the Polynesian rat, *Rattus exulans* (from data in Ref. 38).

effect of radiation on fertility in *Rattus exulans*. The best quantitative data are for the laboratory mouse,(19) in which 50 R of radiation reduced mean litter size of hybrids by about one-third. This is slightly greater than the reduction in R_0 in female albino rats described earlier. In the case of the Engebi rats, it seems reasonable to assume a reduction in fertility of 25 per cent following the 1954 exposure of 65–70 R. The high exposure of 1952, however, may well have killed all the members of the population above ground, half of those that remained in burrows, and reduced the fertility of the remainder by at least 50 per cent. Extrapolating back from a 1955 population of 10,000, and applying these conditions, at least 720 animals had to survive the events of 1952 in order to reestablish the rat population of Engebi.

It is unlikely that a large number of animals would have escaped detection. Personnel of the University of Washington Laboratory of Radiation Biology stated after examination of the island that it was highly unlikely that any of the rats survived on Engebi. If only fifty rats survived, it is possible they would have gone undetected. These animals, with the reduced fertility just considered, would have required an annual multiplication rate $R_a = 5$ for 2 y, and $R_a = 7.7$ for 1 y to attain a population of 10,000 individuals.

These values are reasonable, when compared to the data given in *Pacific Island Rat Ecology*. Even the highest value, $R_a = 7.7$, if it is the result of a 25 per cent reduction in fertility, indicates an approximate maximum of $R_a = 10$.

These figures may represent little more than mental exercise, but they indicate that with reasonable values for rates of increase and for radiation damage to population fertility, a population of fifty survivors in 1952 could have given rise to the population of several thousand observed in 1955. It would be worthwhile to consider experimental application of these methods to populations of *Rattus exulans*.

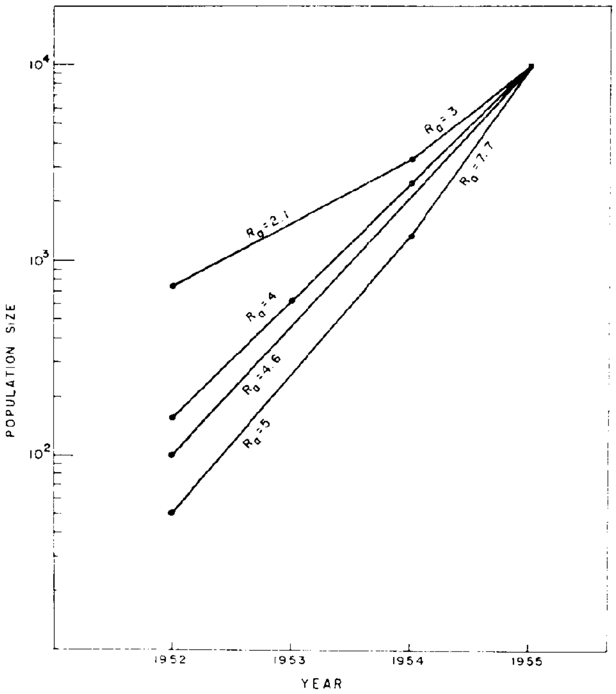

FIG. 4. Annual rates of multiplication required to produce a population of 10,000 *Rattus exulans*.

CONCLUSIONS

These are only illustrations of some methods that may be employed in evaluation of response to radiation or to other environmental stress. Although they have been used primarily as a laboratory tool, there is ample evidence that their application to more complex situations in the field can assist by telling us if our estimates are reasonable and where more information is required.

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RADIATION EFFECTS ON PLANT POPULATIONS AND COMMUNITIES: RESEARCH STATUS AND POTENTIAL

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(*Presented by* R. B. PLATT

Abstract—This paper reviews the research status and future potential for studies concerned with the effects of ionizing radiation on plants at the organism, population, community and ecosystem levels. Opportunities for future development in this field are considered; including experimental techniques and methods for irradiation, dosimetry data retrieval and analysis systems, organisms, homeostatic mechanisms, prediction of radiation effects, physiological stimulation, catastrophic effects of ionizing radiation and effects of continuous low-level irradiation.

INTRODUCTION

THE PURPOSE of this paper is to review the research status and future potential for studies of the effects of ionizing radiation on plants at the organism, population, community and ecosystem levels. Instructions for its preparation were to avoid a review of published work and presentation of unpublished research. Literature references have been omitted; since a literature review is not intended, a few scattered references to support certain points would not be adequate in themselves. For those not familiar with the literature, extensive bibliographies in this field and accounts of research programs in progress have been published by the Environmental Sciences Branch of the Atomic Energy Commission. Information may also be obtained by writing directly to the laboratories referred to in the paper.

What is "radiation effects ecology?" It is simply the study of ionizing radiation effects on organisms in their natural environment. As such, then, it is basic ecology in which ionizing radiation is considered as an environmental stress and includes studies of the effects of radiation on physiological tolerances to environmental stresses, and the manner in which such factors as competitive capacity, susceptibility to parasites, synthesis, reproduction and respiration are affected. At the community and ecosystem levels, studies include dynamics such as energy flow, productivity and succession; structure and composition, such as density, cover and frequency; and interspecific characteristics such as competition between species. Equally important is the study of the ways and rates at which ecosystems recover after irradiation, and the ability of nature's repair and recovery mechanisms to reestablish the balance of nature.

The field of "radiation effects ecology" today has several rather sweeping conditions and changes which may be briefly characterized as follows. First, the motivation and orientation toward such research has rapidly changed. Through its developmental years of the 1950's, the threat of nuclear war, compounded with incomplete and often erroneous information as to radiation hazards and problems, provided a primary stimulus and need for basic and applied research about man and his renewable natural resources. We have gradually shifted our attention from such impending catastrophic events to another phase of ecological problems which are of more immediate concern. These include population control, world food supply, pollution of our natural environment, the use of atomic power, and the exploration and colonization of areas beyond our own planet.

A second characteristic is a shift from predominantly "exploratory" studies to ones of greater depth and sophistication. Research to date has served to establish many "baselines," but the field is still in its formative stages of

Platt, R. B. 1965. Radiation effects on plant populations and communities: research status and potential. Health Physics 11(12):1601-1606.

development, with many of the culminating concepts and broad generalizations yet to be made.

A third trend is that new experimental techniques and methods are rapidly being developed, which are making radiation research possible on campuses and in laboratories without the need for elaborate supporting facilities. Because of these developments, ionizing radiation is becoming a standard laboratory tool, and in time may have the same status as facilities for studying other environmental stresses.

These changing characteristics of radiation ecology are not surprising when one considers that this field is scarcely 10 years old. While studies on the effects of ionizing radiation on organisms date back to the 1930's, and a great deal of work was done through the 1940's and early 1950's, this earlier work was characterized primarily by medical, economic and Civil Defense considerations. An avowed ecological approach to such studies did not develop until the late 1950's, and an estimated 75 per cent of the work has been done since 1960.

EXPERIMENTAL TECHNIQUES AND METHODS FOR IRRADIATION

Four basic methods have been developed for irradiating organisms, populations and ecosystems. A three-dimensional model of an ecosystem, presented in terms of duration, dose rate and dose distribution, illustrates these methods (Fig. 1).

The *first method* consists of short-term exposures from a uniform radiation field. Such exposures would result, for example, from fallout received as a uniform blanket on the surface of the ground, or by some experimental simulation of such fallout, either under laboratory or field conditions. For such a uniform radiation field, the inverse square law does not apply, and radiation dispersion is a function of the coefficient of resistance of the medium through which the radiation travels: $(I = I_0e^{-ud})$. Upward distribution, therefore, is limited only by absorption by air and by any vegetation that may be present. Distribution downward is limited by absorption by the leaf litter and underlying substrate. Since attenuation by air is relatively small, dose distribution above ground from gamma irradiation is relatively uniform, altered primarily by vegetation density. Attenuation downward through the soil is rather sharp with the half-value layer through soil being approximately 3 in., and the tenth-value layer approximately 11 in. The distribution of beta radiation is drastically altered with distance because of its attenuation by air as well as soil. In this method, it is important to recognize that recovery begins immediately upon relief from the stress, whereas the reaction during the stress is primarily one of adjustment to it. To avoid the complexity which would result from both kinds of responses, exposures are usually short enough to avoid any significant adjustment to the stress. Other methods also attempt to elicit only one of these responses, and avoid the problems of interpretation of results when a combination of both are obtained.

The *second method* consists of brief exposures from a point source. In this case, radiation is delivered from a point source such as that obtained in an experimental radiation field, from an unshielded reactor, or from a point source in the laboratory. Dose distribution follows the inverse square law, so that the dose is proportional to the inverse square of the distance and attenuated by the medium through which the radiation passes $\{I = I_0(e^{-ud}D^2\}$. However, if the distance from the radiation source is large in comparison to the distance across the irradiated area, the change across the area (due to the inverse square law) is relatively small. In laboratory situations where the irradiated area is a substantial fraction of the total distance from the source, the dose gradient is of considerable significance. Attenuation by the atmosphere, leaf litter, soil and other environmental materials follows the same rule as for the first method. This second method is the most common, for it lends itself to great diversity, and responses may be sharply identified, particularly when the duration of exposure is a matter of minutes or hours.

The *third method* is a long-term or chronic exposure from a point source. This method differs from the first two in that the stress is continuous rather than temporary. The effects, therefore, primarily consist of an adjustment to the continued stress, rather than recovery

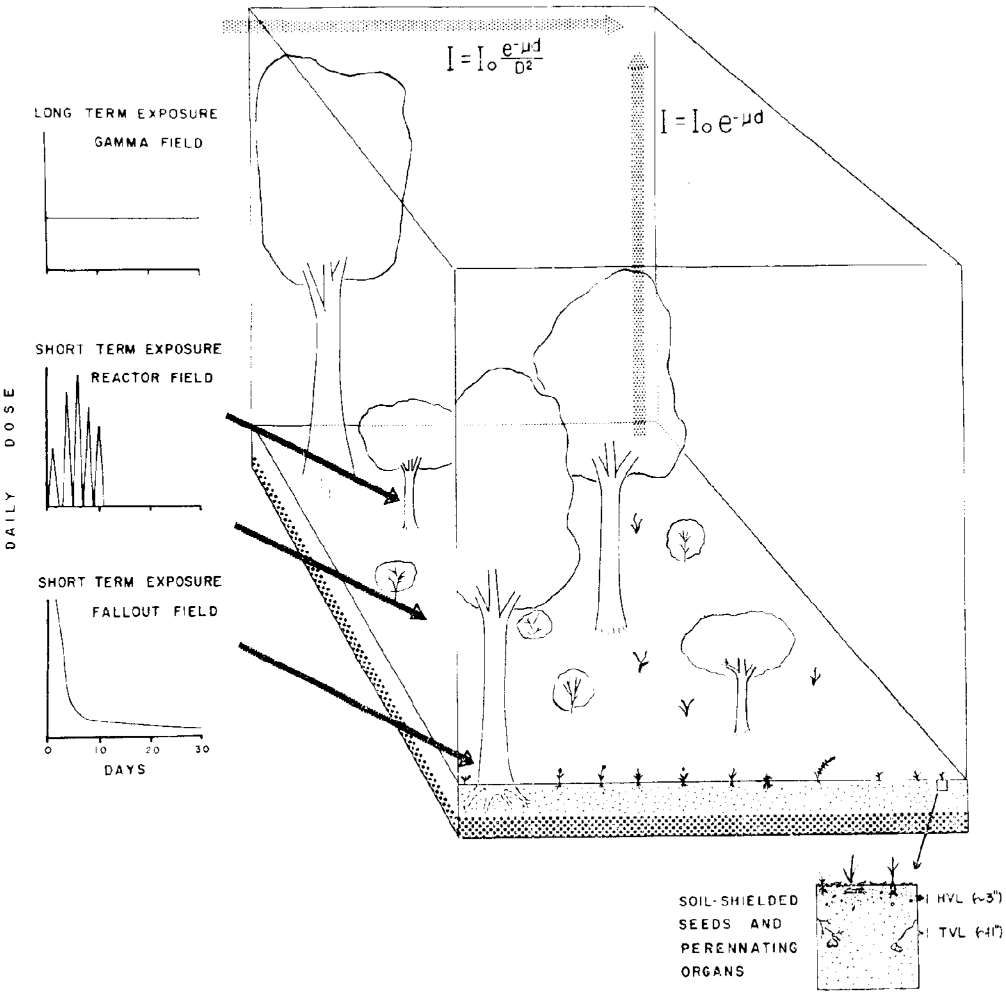

FIG. 1. This three-dimensional model of an ecosystem demonstrates dose characteristics for two sources of radiation, one a uniform blanket of fallout, and the other a point source located away from the area studied. The lower right insert demonstrates environmental shielding of soil organisms, one-half of the radiation being attenuated by about 3 in. of soil, and nine-tenths by about 11 in. The inserts on the left show three kinds of dose rates over a 30-day period.

which is not possible until alleviation of the stress. This method yields data which cannot be obtained from other methods and is of particular significance in the evaluation of responses to a continuous ionizing radiation environment. An ecological analogue would be a hot spring, in which the ecosystem, by adjustment to the continuously high temperature, is quite different from other spring ecosystems. Large scale examples of this method are at Brookhaven National Laboratory and the AEC Nevada Test Site.

A *fourth method* consists of direct radiation from nuclear explosions. Effects from this kind of radiation are very difficult to evaluate. Results from accompanying blast and heat usually have been more severe than that from the irradiation.

Within the last 2 or 3 years, companies have been manufacturing a variety of irradiation sources which may be used in laboratories and greenhouses as well as in the field, and which provide for a great array of experimental conditions. For example, personnel at Oak Ridge National Laboratory have perfected a beta irradiator, which provides a uniform field across the bottom of the irradiator in contrast to a point source. New developments are coming so rapidly in the development of such experimental facilities that they are becoming widely available, and the necessary safeguards as required by the Atomic Energy Commission are more easily provided.

Environmental conditions for irradiation

There is ample evidence that the conditions under which irradiation occurs, as well as the conditions prior and subsequent to irradiation, have a significant effect on the results. This makes it necessary to take these conditions into consideration in a sophisticated manner both in the laboratory and the field to a far greater extent than usually has been the case in past years. These environmental conditions, primarily of temperature, moisture, and light, will interact differently with the organism, depending on its physiological state. Figure 2 is an example of one way by which conditions may be controlled within a radiation field.

Dosimetry

One of the most difficult problems until recently has been the lack of precision methods for determining the actual radiation received by the particular tissue, organism or ecosystem under study. Miniature glass rods and lithium chloride capsules have been developed which make it possible to determine the dose received at a far more definitive level than was previously possible. These have not as yet been used in a sufficient number of cases to firmly establish the peculiarities and characteristics of dose distribution. We can anticipate rapid development in this field, with further substantial improvements in methodology and vastly increased use of such devices in experimental situations.

Data storage, retrieval and analysis systems

Problems in radiation ecology, as in other aspects of ecological research, are subject to an astonishing array of variables. Until the development of modern mathematics, and particularly until the development of high speed computers, ecologists lacked the means of handling this great number of variables. So far there has been little application of such systems to radiation ecology research. Surely, significant developments in this area can be expected in the near future. For example, we are developing plans to use a recently-acquired data storage, retrieval and analysis system on our campus. This system will take physiological and environmental data directly from an experimental facility. At intervals during the experiment, as well as at its conclusion, these data may be retrieved, summarized and correlated on demand. Thus as the experiment proceeds, the results can be followed and the experimental conditions intelligently controlled as dictated by the design.

Increased diversity of experimental organisms

Before 1955, only a few score plants had been used in tests, and these were mostly domesticated plants. Since then the number has been increased several-fold, primarily by the use of wild species. From the standpoint of taxonomic categories, most of the work has been done on seed plants, and knowledge of effects on primitive vascular plants, bryophytes and thallophytes is very meagre. One of the most promising frontiers is that of life below the surface of the ground. Only a handful of papers have appeared dealing with the effects of radiation on the soil microflora and microfauna, and more surprisingly, only a few on the root systems of vascular plants.

Irradiation of ecosystems

Only three approaches to ecosystem research have been developed to date. One is irradiation from atomic testing, which is difficult because it cannot be separated from the effects of heat and blast. A second approach consists of irradiations due to fortuitous circumstances, in which the radiation has been intermittent. Examples of this method are the air-shielded

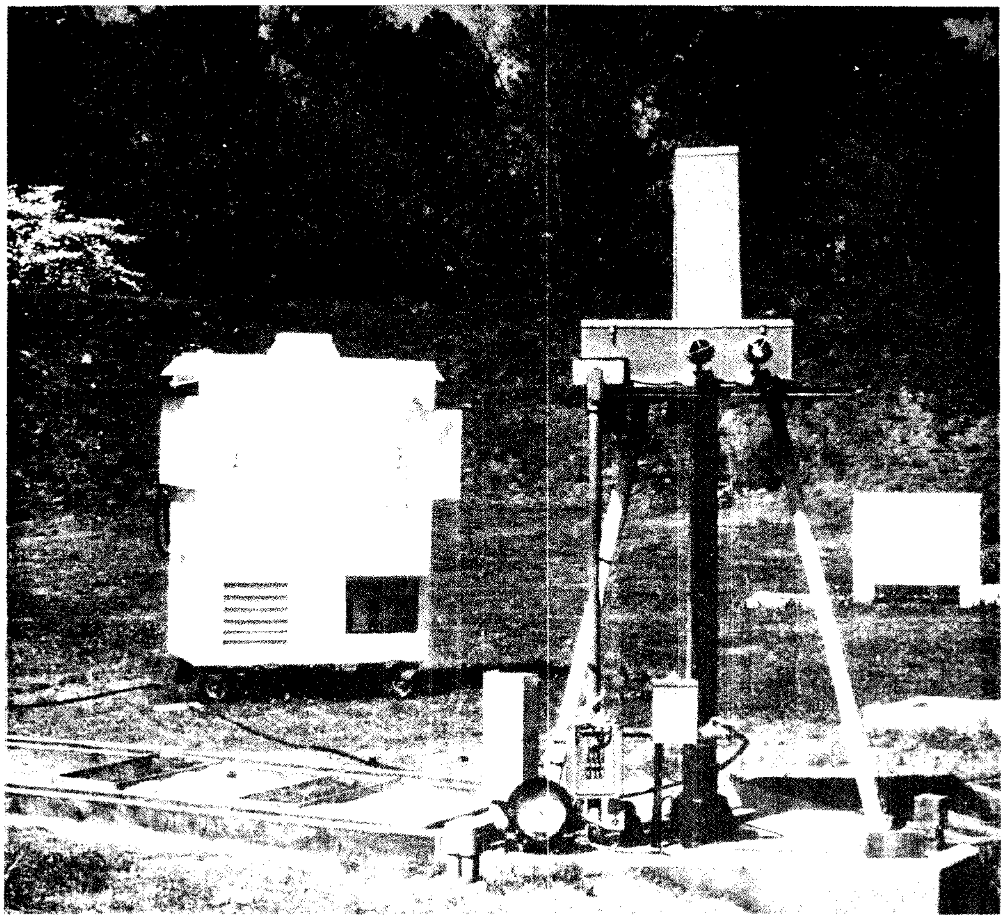

FIG. 2. An experimental chamber in the Emory University gamma irradiation field. The light canopy may be removed to admit sunlight, and the door panels are uniform to prevent radiation shadows or reflections. Combinations of temperature, moisture and light over their full range of natural conditions may be programmed and recorded. Dose is controlled by varying distance and shielding.

reactor built by Lockheed Aircraft Corporation on a 10,000-acre reservation on the upper Piedmont Plateau in Georgia, and the Health Physics reactor at Oak Ridge, which is air-shielded and releases almost pure neutron irradiation into a variety of surrounding ecosystems.

The third avenue of study consists of planned experiments. Two of these employ continuous irradiation, one being the irradiated forest at Brookhaven National Laboratory, and the other the continuous irradiation of a desert ecosystem at the Nevada Test Site. Short-term irradiation is used in the rain forest in Puerto Rico, under the direction of the Puerto Rican Nuclear Center, and in the irradiation of a series of old-field ecosystems at the Institute of Radiation Ecology at the Savannah River Atomic Energy installation.

Therefore, only a very few natural systems have been experimentally irradiated, either in the field or in the laboratory, and there have been almost no studies of other kinds, such as marine and fresh-water, tundra, prairie and alpine ecosystems. A very promising aspect of ecosystem research is the use of small ecosystems which can be experimentally manipulated in the laboratory, such as the small terrestrial "island" communities used by Emory University, or the aquatic ones used at the Savannah River Laboratory.

Homeostatic mechanisms

The term "homeostasis" is used to emphasize the concept that ecosystems, like organisms, have regulatory mechanisms. Homeostasis in ecosystems refers to the mechanisms which enable ecosystems to control themselves in time. Much of the work to date in ecosystem study has been directed toward an understanding of the effects of radiation on these homeostatic mechanisms. Significant studies are being carried out. Because of their longer history, much of the work to date has come from the Oak Ridge, Brookhaven, University of Georgia and Emory University programs.

Physical mechanisms include conditions of the physical environment, such as temperature, moisture and light; nonliving materials; and energy flow. These vary widely between ecosystems, a prominent example being the conditions resulting from the closed canopy of the deciduous forest vs the widely-spaced plants of the desert, which have an open or interrupted canopy. Species diversity, individual species tolerances to various environmental conditions, energy flow, and productivity are highly significant mechanisms. Finally there are the biological interactions between populations, including growth rate, growth form, age, distribution, physiological state, competition, predation and parasitism.

Prediction of radiation effects

Up to the present time, the primary breakthrough in prediction of radiation effects has been based on the nuclear characteristics of the organisms receiving radiation. Under laboratory conditions, dose-effect correlation is high for these characteristics. However, they have had limited use in ecological situations, for they are but one input into the response of the organism. In the laboratory, these other environmental variables may be controlled, but in nature this is impossible. Here wide variations occur and combinations of variations occur which often override the responses arising from nuclear characteristics. In addition, there are many other aspects of stimulus-response systems to be worked out, many of which have hardly been touched. Figure 3 is a conceptual diagram which illustrates the diversity of conditions which must be considered in evaluating and predicting such responses under natural conditions. While the baselines for such responses can best be worked out under laboratory conditions, their ultimate impact has its significance not in the laboratory, but in the field. Predictions within useful range of accuracy have been and are being made.

Definitive studies on physiological stimulation

Stimulatory effects of ionizing radiation on plant growth has been a subject of considerable interest and debate for a number of years. Stimulation has been reported by competent investigators from many laboratories, both in this country and in the Soviet Union. However, we still know very little of its nature and extent. Definitive studies aimed specifically at this phenomenon are needed, particularly those which systematically eliminate all other factors

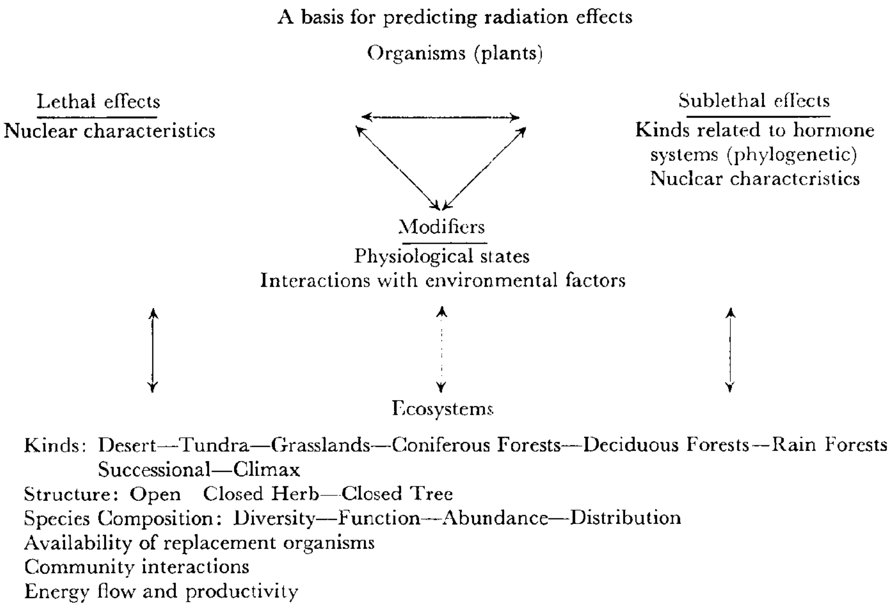
A basis for predicting radiation effects
Organisms (plants)
Lethal effects
Nuclear characteristics
Sublethal effects
Kinds related to hormone systems (phylogenetic)
Nuclear characteristics
Modifiers
Physiological states
Interactions with environmental factors
Ecosystems
Kinds: Desert—Tundra—Grasslands—Coniferous Forests—Deciduous Forests—Rain Forests
Successional—Climax
Structure: Open Closed Herb—Closed Tree
Species Composition: Diversity—Function—Abundance—Distribution
Availability of replacement organisms
Community interactions
Energy flow and productivity

FIG. 3. This diagram demonstrates the homeostatic mechanisms which control the effects of radiation stress, the upper part relating to plants and the lower to ecosystems. Conversely, an evaluation of these factors is relevant to the prediction of radiation effects.

or combinations of factors, thus leaving the cause and effect relationship of radiation-stimulation as the focal point of study.

Catastrophic effects of ionizing radiation

Levels of ionizing radiation sufficient to bring about catastrophic effects similar to those from nuclear war have been difficult to carry out. The irradiated ecosystems at Emory University, Brookhaven National Laboratory and Puerto Rico Nuclear Center provide the best experimental evidence to date. However, an indirect approach to this problem is being carried out by the use of ecological analogues. Certainly ecosystems should respond to high intensity ionizing radiation stress in somewhat the same way as they would to hurricanes, floods, severe insect attacks and abrupt changes in climate. Several such analogues have been made and others will most likely be developed in the future.

Effects of continuous low-level irradiation

Data on effects of continuous low level radiation have been sharply limited because of our inability to measure such effects, either qualitatively or quantitatively. Although much thought has been given to the biological importance of background terrestrial radiation, results reported at this particular session represent one of the first definitive studies on the biological role of background terrestrial radiation as a constituent of the natural environment. At levels somewhat higher than background, the experimental irradiation project on the desert ecosystem at the Nevada Test Site is providing an experimental basis for such studies. The problem is twofold. On the one hand is that of radiation received directly from the environment, while on the other is that of the internal dose resulting from physiological assimilation of radioactive nuclides.

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UNSOLVED PROBLEMS OF WATER RADIOECOLOGY

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On the basis of an analysis of the modern state of investigations in the field of the radioecology of water organisms, its most important unsolved problems, associated with determining the role of the physicochemical state of radionuclides in the radioecological processes of concentrations, disclosing the mechanisms of the penetration, accumulation, and distribution of radionuclides in living systems and the participation of radioecology in the protection of nature are discussed.

By now the number of questions on which radioecologists are working has increased sharply. The considerable material accumulated on a whole series of divisions of water ecology is evidence of the successes of this comparatively young branch, common to radiobiology and hydrobiology. The basic results of the progress made have been summarized at recent radioecological forms: the International Symposium on Continental Radioecology in 1969 (Cadarash, France), the All-Union Symposium on the Radioecology of Aquatic Organisms in Their Communities in 1968 (Miassovo, USSR), and the Second National Symposium on Radioecology in 1967 (Ann Arbor, United States).

In this article the main attention is paid to the most important unresolved problems of water radioecology, which include: 1) the problem of the physicochemical state of radionuclides in the medium (and its significance for processes of absorption of these substances by organisms), 2) the problem of the mechanisms of the accumulation of radioactive substances by hydrobionts, and 3) the problem of protection of living nature from radioactive pollution.

Polikarpov, G. G. 1970. Unsolved problems of water radioecology. Radiobiologiya 10(2):242-252. (1970. English transl. AEC-tr-7171; pp. 121-137).

All these three great complex problems are characterized at the present stage by insufficient material and the resultant dispute over a whole series of existing conclusions.

PHYSICOCHEMICAL STATE OF RADIONUCLIDES

The study of this problem, from the standpoint of radioecology, is of dual significance. First of all, since the accumulation of a chemical element by a hydrobiont depends on its state and form in water, it is extremely desirable to know in each case with what state and form of the radionuclide one must deal. Furthermore, some states are dynamic, whereas others are extremely stable. Finally, it is important to have information on whether the radionuclide exists in the same state and form as its chemical element and, if not, how rapidly there is a transition to the stable state and form of the latter in aqueous medium. Without such information it is impossible to use radionuclides as radioactive tracers (labeled atoms) with assurance in the study of the circulation of chemical substances in biogeocoenoses.

Let us explain the considerations cited above by materials obtained at the Division of Radiobiology of the Institute of the Biology of the Southern Seas of the Academy of Sciences Ukrainian SSR. In Fig. 1 it is shown that the accumulation of thallium-204 depends substantially on the chemical forms and physicochemical state of the introduced radionuclide [1]. Thallium (trivalent), introduced from sulfuric acid solution, is accmulated by the green alga *Ulva rigida* with an accumulation factor substantially higher than that from alkaline solution (pH > 10). Figures 2 and 3 demonstrate the complex dynamic picture of the change in the physicochemical state of yttrium-91 and yttrium-90 with time [2, 4], while Fig. 4 reflects the stability of the state of zinc in sea water during the period studied -- 10 days (according to the data of V. N. Ivanov, L. I. Rozhanskaya, and L. N. Leshchenko).

Extremely surprising data were obtained by Italian scientists [4]: the coefficients of accumulation of cesium-137 (from fallout) in fishes from various lakes of Northern Italy were an average of 3.3 times higher than those of stable cesium (Table 1). These results were obtained on extensive material in a period of seven years of systematic investigations. On the other hand, experiments are known [5] in the United States with cesium-137 (from wastes), in which no difference was detected in the coefficients of accumulation of radioactive and stable cesium. Therefore, C. Polvani et al. [4, 6] suggested that the physicochemical state of cesium-137 from fallout on the one hand, differ from that of stable cesium and cesium-137 from wastes, on the other, which is confirmed by a direct study of this state in cesium of different origins. Thus, stable cesium may exist in lake water chiefly in the form of ions.

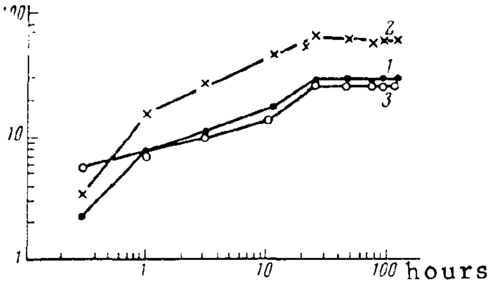

Fig. 1. Kinetics of the accumulation of ^{204}Tl by the green alga *Ulva rigida* [1]. Along X-axis -- time from beginning of experiment; along Y-axis -- coefficients of accumulation. 1 -- Univalent ^{204}Tl, introduced from nitric acid solution, pH 8.3; 2 -- trivalent ^{204}Tl, introduced from sulfuric acid solution, pH 8.3; 3 -- trivalent ^{204}Tl, introduced from alkaline solution, pH 11.5; $C = 10^{-6}$ M.

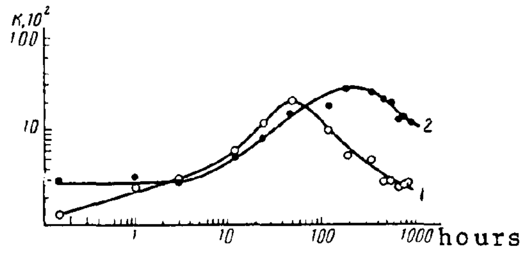

Fig. 2. Change in the values of the coefficient of adsorption on the hydrophobic polymer adsorbent teflon of ^{91}Y (1) and ^{90}Y (2) from a mixture of them as a function of the time of "aging" of the solution [2, 3]. Along X-axis -- time from beginning of experiment; along Y-axis -- coefficients of adsorption.

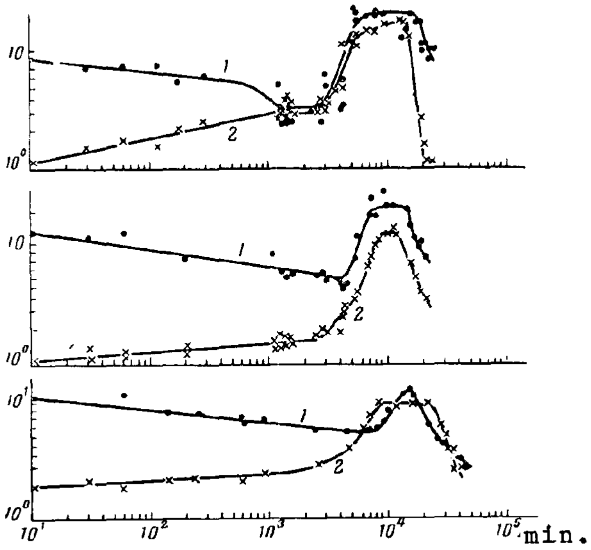

Fig. 3. Change in the values of the coefficients of accumulation of radioyttrium by *Ulva rigida* (1) and coefficients of adsorption on teflon (2) [2, 3]. Along X-axis -- time from beginning of experiment; along Y-axis -- coefficients of accumulation and adsorption.

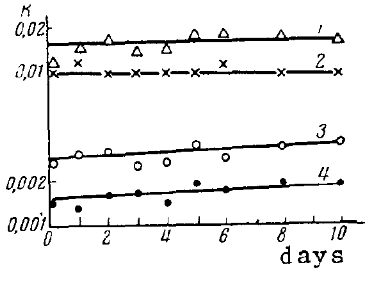

Fig. 4. Change in the adsorption properties of zinc-65 with time (data of V. N. Ivanov, L. I. Rozhanskaya, and L. N. Lishchenko). Along X-axis -- time from beginning of experiment; along Y-axis -- coefficients of adsorption. 1 -- adsorption on glass from Black Sea waters; 2 -- from ocean water; 3 -- adsorption on teflon from Black Sea water; 4 -- from ocean water.

In our opinion, the results cited in [4, 6] refute the existing complex hypothesis of the presence of barriers in the organism permeable to stable and impermeable to radioactive cesium, permit a different treatment of the rate of exchange and migration of the latter along food chains, and also compel a more cautious use of the concept of the specific activity of the radioisotope (the ratio of the number of atoms of a radioactive isotope to the total number of atoms of the element).

Table 1

Coefficients of Accumulation (CA) of Cesium-137 (from Fallout) and Stable Cesium [4]

Species	Lakes			
	Maggiore	Varese	Comabbio	Monate
Perca fluviatilis				
CA of ^{137}Cs	2550	1170	2150	4670
CA of Cs	1370	120	840	1190
Ratio*	1.9	9.8	2.6	3.9
Scardinius erythrophtalmus				
CA of ^{137}Cs	1200	860	910	1330
CA of Cs	630	150	440	430
Ratio*	1.9	5.7	1.1	3.1
Lepomis gibbosus				
CA of ^{137}Cs	580	390	650	2500
CA of Cs	530	120	430	820
Ratio*	1.1	3.3	1.5	3.1

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*The average ratio is equal to 3.3.

Thus, it still remains to determine the principles of the change in the physicochemical states and forms of various radionuclides, to determine the states and forms of chemical elements in various conditions of the water medium (of the type of a body of water) and, therefore, bridge the gap from radioactive to stable (natural) nuclides of each chemical element. Here will be one of the major contributions of radioecology to chemical ecology, in addition to the solution of problems of direct interest to radioecology itself, the end purpose of which is the elucidation of the principles of the action of incorporated and external emitters on the communities of living organisms.

MECHANISMS OF THE ACCUMULATION OF RADIONUCLIDES

The problem of the mechanisms of the accumulation of radionuclides by living systems is exceptionally complex, since it involves all levels of organization of living matter, from the macromolecular to the biogeocoenotic. Actually, radionuclides of known states and form interact with the surfaces of cells, can be incorporated into the structural formations of the latter, participate in ecological (interorganismic) metabolism or be transmitted along food chains, distributed, and migrate in populations, biocoenoses, biogeocoenoses, and the biosphere.

It is extremely important to determine the quantitative role of adsorption in the radioecological processes of accumulation of nuclides. It goes without saying that for radionuclides in different physicochemical states and forms, it will differ. Work along this line holds great promise. According to the data of V. I. Ivanov [7], processes of adsorption determine the values of the coefficients of accumulation of yttrium-90, yttrium-91, and cerium-144 by the roe of marine fishes and play a significant role in the initial period of accumulation of radiozinc by the green alga *Ulva rigida*.

The disclosure of the molecular-physiological processes of the penetration of radionuclides into the cell [8, 9], characterized by kinetic and energy dependences, permit an establishment of the laws of the exchange of radionuclides in its structures. G. V. Barinov is working on this difficult problem [8, 9]. Here the word "exchange" is intentionally used instead of "accumulation," for the following reasons. In individual, and perhaps in a whole series of cases, there is no need of processes of vital activity for a bioaccumulation of certain radionuclides to occur. Thus, we have shown that strontium-90 is accumulated by the killed brown alga *Cystozira*, just as the living form. This phenomenon has also been confirmed by other coworkers of the Division of Radiobiology of the Institute of the Biology of the Southern Seas of the Academy of Sciences Ukrainian SSR. It has been suggested that the process of accumulation of strontium-90 by *Cystozira* is associated with its rather stable structures.

In experiments (Fig. 5) conducted by G. E. Lazorenko, it was shown that at pH 3, which is characteristic of cells of brown algae, strontium-90, as well as cerium-144, are concentrated by algic acids in vitro to high values of the accumulation factors (100 and 500, respectively). Zinc-65 and thallium-204 are not extracted by it at all. Obviously these are only the first model experiments, but, in our opinion, they are being conducted in the proper way -- the search for the simplest mechanisms of the deposition of radioactive substances. Their reproduction in actual models once again can give a large practical yield in a new field -- chemical hydrobionts. As yet only a few are lending their efforts to it: L. G. Kulebakina, D. D. Rȳndina, G. E. Lazorenko and certain others.

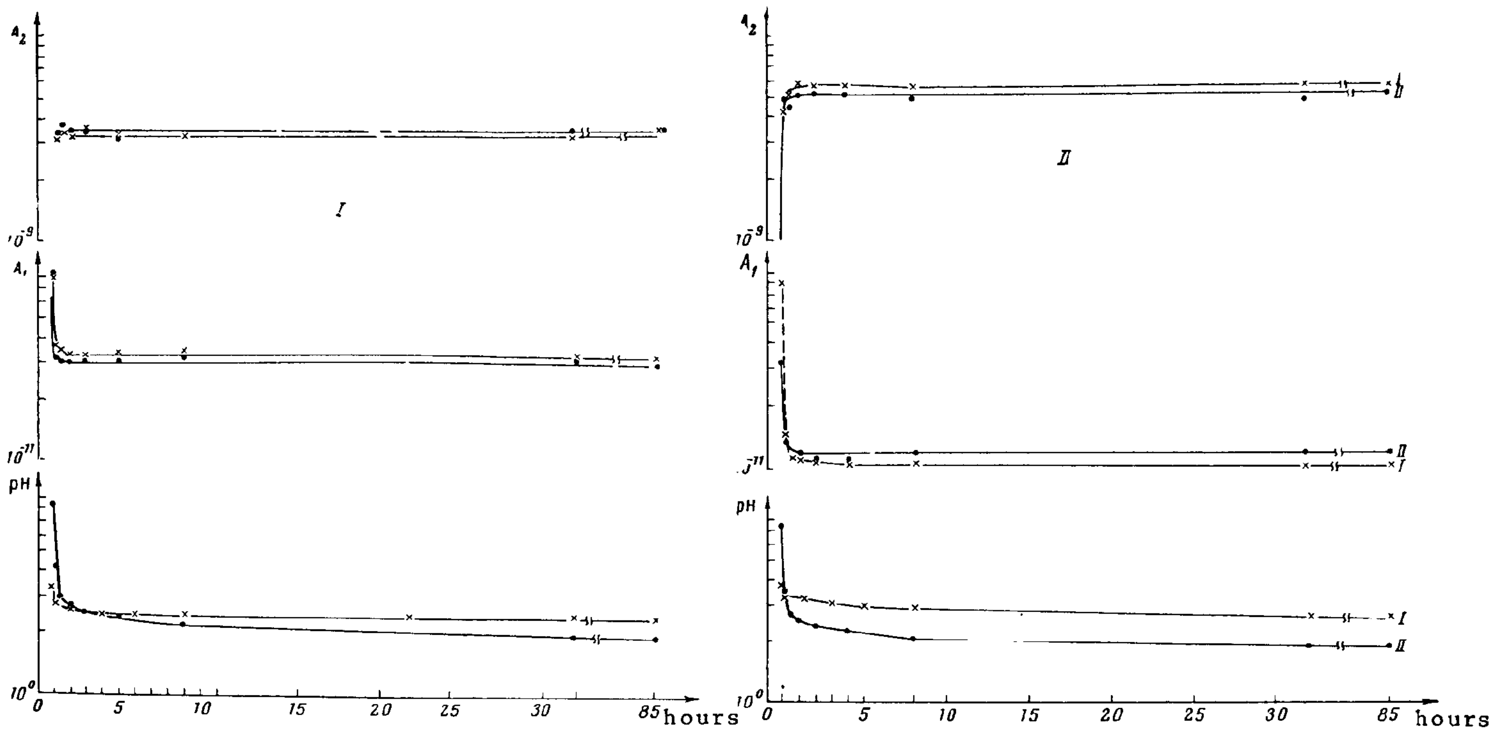

Fig. 5. Penetration of strontium-90 (I) and cerium-144 (II) into algic acid from sea water. Along Y-axis -- time from beginning of experiment; along Y-axis: pH, A_1 -- concentration in sea water, 10^{-11} Ci/ml, A_2 -- in algic acid, 10^{-9} Ci/g.

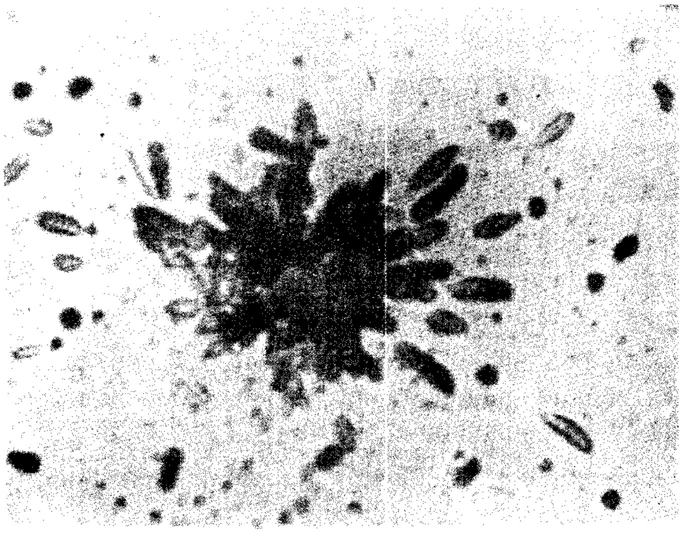

Fig. 6. Depiction of lavsan of the microaccumulation of uranium in plankton of a fresh-water lake [10].

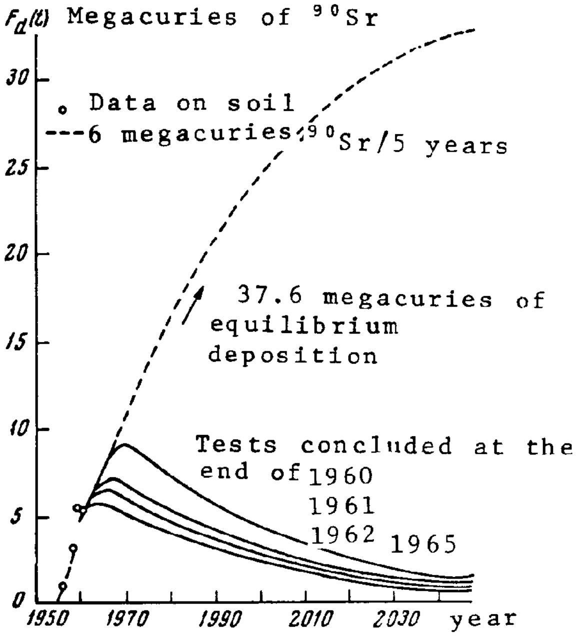

Fig. 7. Future deposits of strontium-90 [20].

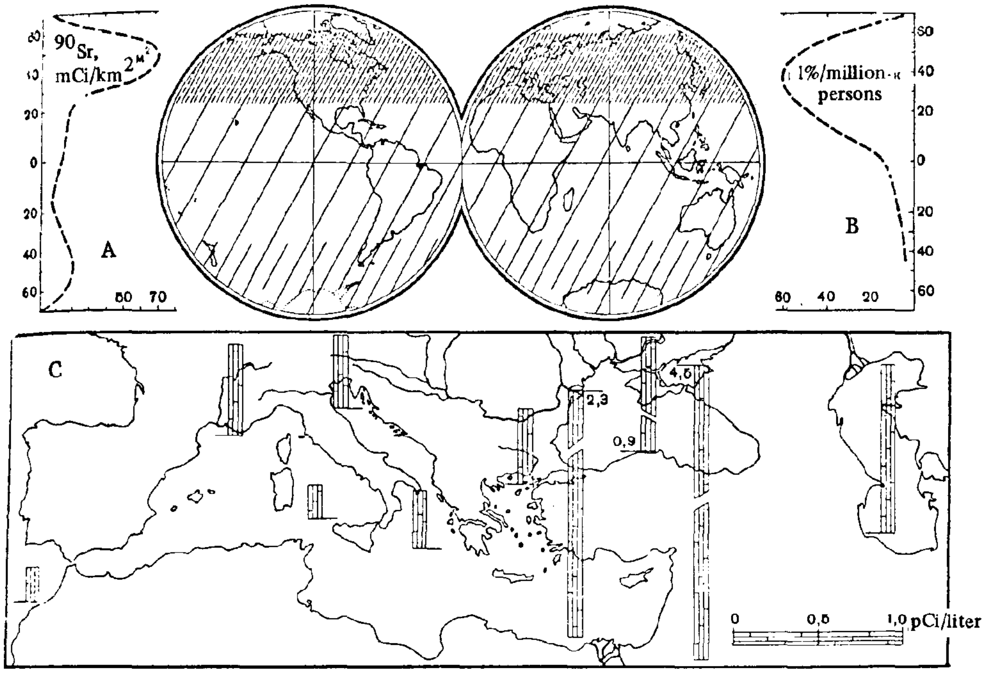

Fig. 8. Geographical macro- and microdistribution of strontium-90 in the biosphere. A, B -- density of its fallout on the surface of the earth [21] and population density [22] at various latitudes; C -- uniformity of distribution of strontium-90 in one of the latitude bands (with the seas of the Mediterranean basin as an example) [23, 24].

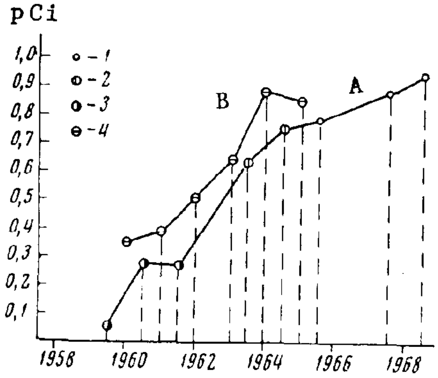

Fig. 9. Increase in concentrations of strontium-90 (pCi/liter) in the Black (A) and Baltic (B) Seas. According to the data of 1 -- [24], 2 -- [25], 3 -- [26], 4 -- [27].

The phenomenon of microaccumulation of uranium in hydrobionts (Fig. 6), detected by N. S. Risik [10], was a great event in radioecology. It raises at least two problems: 1) to evaluate the extreme nonuniformity of the "microgeometry" of the doses in the cells and tissues on account of α-particles with very large local maxima; 2) to determine the causes of the formation of such "stars" or "hedgehogs" of uranium and to attempt to develop methods for the detection of possible microaccumulations of other radionuclides.

There are varied viewpoints concerning the pathways of penetration of radionuclides into the bodies of water animals, in view of the extreme insufficiency of investigations. K. Kimura and R. Ichikawa [11] emphasize that "there has been very little quantitative information on the transfer of radioactive substances along food chains up to the present time" (p. 434). D. G. Fleĭshman [12], on the basis of the ratio of the cesium-137 and stable cesium concentrations in hydrobionts of Lake Dal'nȳi, concludes that cesium-137 (and stable cesium) penetrate into the bodies of water animals only with the food. However, as has already been noted above, cesium-137 can behave differently in lakes from natural cesium [4, 6]. Therefore, there is not yet sufficient basis for the categorical conclusion cited above [12].

D. P. Marchyulenene [13], in experiments with various radionuclides on aquatic larvae of insects, fresh water bivalve mollusks, and fishes, discovered that the basic source of absorbed radionuclide, at least during a period of two weeks, is radioactive water, and not radioactive food. The same conclusion was drawn by Japanese researchers in [11], studying the accumulation of ruthenium-106 by marine fishes from radioactive marine worms and sea water.

To arrive at an unambiguous conclusion on the pathways of penetration of various radioactive substances (and for general biology -- chemical elements) into the bodies of hydrobionts is an urgent problem of radioecologists, studying the role of trophic conditions in the distribution and migration of radionuclides in bodies of water.

RADIOECOLOGY IN THE SERVICE OF PROTECTION OF NATURE

As is well known, man is exerting an ever-increasing pressure upon the animal and plant world of our planet [14-16]. Radioactive pollution makes its own contribution to the general pollution of the biosphere. For this reason, the well-known scientists in the field of the protection of nature, J. Dorst, writes that man "...in the future should not spare any effort toward protecting living nature from the threat of atomic 'pollution,' in comparison with which all other forms of pollution of the earth, water, and air seem like only children's toys" [17]. Actually, in contrast to other types of pollution, artificial radioactive substances represent a new and extremely specific factor [18]. Moreover, unusually high concentrations of natural radioactive substances are being involved in the general circulation of chemical elements in the biosphere in connection with industrial activity [19].

As is well known, most countries have adopted the resolution to stop nuclear testing in space, in the atmosphere, and under water (Moscow, 1964). Scientists of various specialties have played the chief role in bringing about this important act. The contribution that has been made by radioecologists and geneticists would be difficult to exaggerate. A systematic study of global radioactive fallout on account of tests of atomic devices led to the creation of prognoses of further pollution of the earth's surface under various conditions (Fig. 7) [20]. According to our calculations, the amount of strontium-90 in the biosphere (global and local fallout) in 1963 was estimated at 12 million Ci, including 10 MCi in the world's ocean. The total amount of strontium-90, cesium-137, and other more short-lived radionuclides, injected into the external environment, was tens of MCi in 1963.

Of great importance for radioecology is the law of uniform distribution of radioactive fallout at the surface of our planet (Fig. 8, A, B) [21-24]. In the zone of the highest density of radioactive pollution (30°-50° N. lat.), in turn, regions with various concentrations of radionuclides are observed. Let us explain this with one of the concrete examples of the investigations conducted by the Institute of the Biology of the Southern Seas of the Academy of Sciences of the Ukrainian SSR (Fig. 8, C). Thus, in 1968 various concentrations of strontium-90 were detected in the surface waters of the Mediterranean basin, decreasing from east to west from 0.9 to 0.25 pCi/liter [23, 24].

It is extremely important to turn our attention to the fact that, despite the sharp drop in the amount of radioactive pollution injected into the external environment (in connection with the limitation of nuclear testing), in a whole series of regions of the biosphere, as a result of their characteristic peculiarities, no decrease is observed in the concentration of strontium-90 -- one of the basic long-lived fragment radionuclides. These include, for example, seas possessing weak water exchange with oceans (Fig. 9) [24-27]. The drainage of radionuclides into the sea by rivers, especially those possessing a large area of water collection (for example, the Dunaĭ for the Black Sea) may make its own contribution to this process. Investigations of this kind should receive all possible support.

Animals inhabiting zones of one level of radioactive pollution pass into zones with other levels during processes of circadian, seasonal, and ontogenetic migrations. Larvae of gray mullets, for example, after hatching in zones of the open sea with the least strontium-90 concentrations, travel along a gradient of increasing concentrations of it into the zones of browsing (Fig. 10) [24, 28].

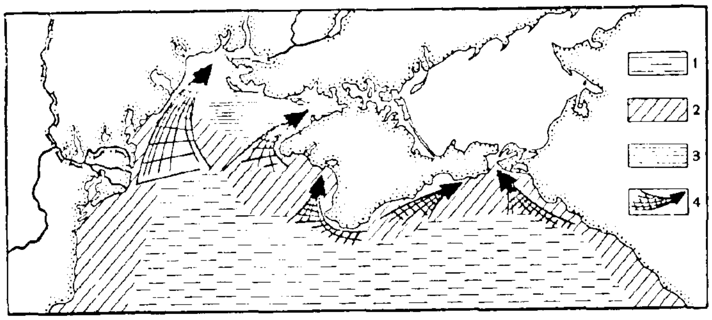

Fig. 10. Distribution of strontium-90 concentrations in the northern portion of the Black Sea [24] and pathways of migration of gray mullet fry [28]. 1 -- range of 0.75-1.00 pCi/liter; 2 -- 1.0-1.5; 3 -- more than 1.6 pCi/liter; 4 -- directions of the displacement of schools of sharp-nosed gray mullet fry.

Although there is definite unanimity with respect to nuclear testing in various compounds, a different situation prevails with respect to the question of the removal of radioactive wastes of atomic enterprises. Here each country approaches it in its own way. However, unfortunately most governments resolve this important problem on the basis, primarily, of economic considerations (the cheapest method of removal of wastes).

There is no need to undertake an estimation of the amount of radioactive wastes discarded by various countries within their own territory. This is an internal affair of each state. Most important is the international aspect of the problem of removal of radioactive wastes, namely: when wastes are discarded into rivers flowing along the territories of many countries, into international waters of the seas, and into oceans.

We must also mention a third potential source of radioactive pollution to a high degree -- possible nuclear conflict.

Table 2

Summary Data on the Influence of Low Doses of Irradiation by Incorporated Radionuclides on the Chromosomal Apparatus of Animals and Plants [32]

Calculated absorbed dose, mrad	Excess over absorbed dose on account of cosmic background*	Object	Frequency of anomalous mitoses, % of control	Source
0.3-10	up to 10^2	Sea urchin and sole-turbot (roe)	128-226	[32]
$10-10^2$	up to 10^3	Rats (bone marrow)	138	[33]
$10-10^2$	up to 10^3	Sea urchin (roe)	128-188	[32]
10^2-10^3	up to 10^4	Rats (bone marrow)	175	[33]
10^2-10^3	up to 10^4	Sea urchin and sole-turbot (roe)	175-242	[32]
10^3-10^4	up to 10^5	Rats (bone marrow)	236-616	[33]
10^3-10^4	up to 10^5	Sea urchin (roe)	230	[32]
10^3-10^4	up to 10^5	Kapital peas (rootlets grown from seeds soaked in solutions of radionuclides)	295**	[34]
10^3-10^4	up to 10^5	Broad beans (meristem of growing point of stem)	1160-1263	[29]
10^4-10^5	up to 10^6	Rats (bone marrow)	212	[35]
10^4-10^5	up to 10^6	Rats (epithelium of mucous membrane of small intestine)	195	[36]
10^4-10^5	up to 10^6	Sole-turbot (roe)	165	[32]
10^4-10^5	up to 10^6	Kapital peas (rootlets grown from seeds soaked in solutions of radionuclides)	227-439**	[34]

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*Absorbed dose on account of cosmic radiation comprises 0.1 mrad/day.

**Against a background of increased mitotic activity.

Note. The inhibition of growth and development of broad beans *Vicia faba* and destructive changes in the sex glands of field mice *Microtus oeconomus* was observed with a dose rate of 0.1-4.0 mrad/hr on areas with an increased content of radioactive substances in the environment [30-31]; a dose of 0.2-0.5 R per year (≈2-1 mR/day) produced an almost fourfold increase in the number of chromosomal aberrations in human leukocytes in comparison with the control [37].

In evaluating the radioactive pollution of the external environment, the main attention is paid to the radiation hazard to man. This is entirely correct and essential, but insufficient, since man is a part of nature. Radiation hygienists have developed maximum permissible concentrations of radionuclides (MPC) for man in fresh water considering the accumulating ability of hydrobionts that consume it in food. Various countries, including the USSR, have an MPC in fresh water. MPC in sea water have been adopted in the United States, England, India, and other nations. D. I. Gusev reported on the MPC of radionuclides in sea water at the All-Union Symposium on the Radioecology of Fish Roe back in 1966 (Sevastopol). At the Session of the Scientific Council "Radiobiology" of the Academy of Sciences USSR, devoted to problems of radioecology, in 1969 (Leningrad), the need for MPC of radioactive substances in sea water, adopted in our country, was again emphasized.

As for the nature surrounding man, the establishment of the MPC of radionuclides for living organisms themselves has been paid practically no attention. And yet, the extremely high sensitivity of organisms to incorporated radionuclides has been noted by many researchers [29-31]. V. G. Tsȳtsugina [32] has summarized the available literature data on the results of investigations of the effects of low doses of irradiation by incorporated radionuclides on the chromosomal apparatus of certain animals and plants (Table 2), an analysis of which emphasizes the urgency of further research in this difficult field. In our opinion, the basic stress should be placed in the future on radiation genetic investigations. MPC of radionuclides for living organisms are absolutely essential, since we are attempting to protect living nature from the harmful effects of the radioecological factor.

Such are the basic problems of radioecology in the matter of the protection of nature. To ensure effective radiation safety of the biosphere, in our opinion, it is essential to show more scientific caution than disregard of danger or haste in conclusions and actions. It should always be recalled that our biosphere is unique and, therefore, a mistake with regard to it (uncorrectable disturbances in the structure and functioning of living systems, possible radiation impact with respect to man, etc.) would be fatal.

The further vigorous growth of nuclear energetics, transport with nuclear engines, and the use of nuclear energy in the national economy will require an intensification and acceleration of radioecological investigations at an ever-expanding scale.

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CONTRIBUTIONS OF RADIOECOLOGY TO AEC MISSION PROGRAMS[1]

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Any discussion of the contributions of a scientific activity to technological goals and objectives involves a certain degree of value judgement - value judgement, not of the technological objective, since such objectives are derived rather directly from societal needs, but rather judgement of the science. Value judgement in science is both old and new. It falls under the philosophical domain of axiology, which deals with the theory of value, including ethics and aesthetics.

Recently in a thoughtful essay, Weinberg (1971) points out that the axiology of science is an area that should be of interest to scientific administration in its most fundamental aspect, namely, the allocation of scientific resources. Irrespective of the level of administration, whether at the scientist working level or at the office of management and budget level, the question of value is pervasive. The problem of value in science is timely. Reductions in science budgets have raised fundamental questions of priority in allocation of funds for research support. As a consequence science administrators at all levels are under continuing pressure to make sharp and painful choices between areas of science for priority support.

It is, therefore, especially appropriate at this time to examine the contributions and accomplishments of radioecology in the context of axiology. Nuclear energy and its related developments constitute an important segment of the public's concern about environmental quality in general, and environmental pollution in particular.

In making this a posteriori evaluation, the bases for judgement of radioecology as a scientific field include the facts, knowledge, and paradigms which have contributed toward the development of a safe and acceptable nuclear technology. Additionally, as discussed by the previous speaker, radioecology has met another important axiological criterion. This is the criterion associated with its contribution to related fields and disciplines. To the extent that advances in knowledge or new methodologies have served the general field of ecology and its several subdisciplines, this too represents another axiological consideration.

What are the AEC missions which have engendered the need for radioecological research? Like many research and development areas which bear strongly on societal interest and response, AEC missions have tended to vary in time in accordance with social attitudes, needs, or interests. Just as these mission needs have shifted temporally, so has the research in radioecology shifted historically. The causal factors are relevant only in that they serve as partial explanation for some of the diversities and emphases of radioecological research.

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The First National Symposium on Radioecology, held in 1961, provided ecologists with a framework of tasks, the response to which constitutes the main body of effort that we now recognize as radioecology. In his eloquent opening remarks to that Symposium, Wolfe (1963) outlined five major areas of nuclear energy effort wherein ecological knowledge and understanding were needed. These five areas were fallout from military testing, reactor development, radioactive waste disposal, nuclear war, and technological projects such as Plowshare.

Ionizing radiation, including its indirect as well as its direct effects on natural systems of organisms and man, was and still is the pervasive problem in all of these nuclear areas. The dose to man, as effected by or through the network of biological and related physical processes that make up the landscape mosaic of ecosystems, was, and remains, another major mission area of pertinence to the AEC. If ionizing radiation be the warp, then ecosystem behavior and manipulation of radionuclides is the woof of the environmental problem fabric that clothes nuclear technology. Unlike the emperor's new clothes, this fabric exists, not only in the eyes of the wearer but even more strikingly in the eyes of the citizen beholder.

Radioecology received its major impetus in the mid-1950's, although a number of pioneering efforts and small programs had been under way at several AEC installations. Radiobiology was making notable factual and theoretical contributions to our knowledge of radiation damage by use of laboratory organisms. Agricultural radiobiology was pursuing roughly parallel interests. Military testing with its overtones of nuclear war, reactor development for power and propulsion, and radioisotope development for a variety of domestic uses provided adequate justification for the activity in radiobiology.

Knowledge about the effects of radioactivity on the environment was meagre. Interest in the need for such knowledge was also meagre. This was understandable, since the history of all science, irrespective of the disciplines, teaches us that the practioners of science tend to judge the relative merits and needs of science within the context of their own areas of knowledge.

Nuclear war and weapon's fallout were profound concerns at the time of formal establishment of AEC programs in radioecology. Little was known about the radiosensitivity of organisms in the environment, especially higher plants and mammals. How much radiation was required to damage a forest? Are red oaks more sensitive than yellow pine? How do grasslands compare in their radiosensitivity with deciduous forests? How are the structure and function of these complex ecosystems affected by both total dose and dose rate? Is there recovery of the systems and what are the time constants involved? These questions are examples of many related ones where facts were needed at that time and where such knowledge could not be derived from the laboratory data available. The obvious lack of answers to such questions and the initiation of an ecological program in the AEC provided a basis for much needed research.

It remained for ecologists such as Platt and his students, Woodwell and his group, Sparrow, and Witherspoon, among others, to provide many of the answers to these questions. As a result of their investigations, we now know in general terms the likely effect that massive doses of gamma radiation would have on important segments of our landscape. Likewise, we now know a great deal about the specific responses of many higher plant taxa to both dose and dose rate within an environmental context.

How has this information contributed to the AEC missions? For one thing these data demonstrated that our natural environment, as characterized by the dominant vegetation, is a mosaic of varying radiosensitivities - representing not only the intrinsic biological response of the species but also the effect of physical environmental variables and the interaction of both biological and physical factors. These data on plant response to ionizing radiation, particularly gamma and fast neutron radiation, enabled radioecologists to evaluate, in a preliminary fashion, the immediate consequences of a nuclear attack on the

United States. The longer-term sequelae of events following a moderate or large-scale attack are still clouded with many uncertainties. But given support and interests, this particular aspect of the nuclear war problem also is amenable to ecological study and synthesis. Such studies would help relate the problems of societal recovery to the recovery of our renewable natural resources.

More recently the importance of the intense beta fallout that follows a nuclear explosion has been recognized. The dose from beta particles in the immediate fallout zones has been calculated to be 40 to 90 times the immediate gamma dose rate. Although beta radiation is not as penetrating as gamma radiation, the dose to superficial tissues and sensitive organs such as buds can be considerable. Rhoads, Platt, Witherspoon, McCormick, and other plant radioecologists have already obtained the necessary data to define the nature of the problem both ecologically as well as radiobiologically. Preliminary predictions on landscape consequences in terms of a given weapon size have been made by these workers. Again, as with gamma radiation, determining the long-term consequences as well as the impact of large-scale attacks remains as a challenging problem.

Fallout from weapons tests was, if one can express it thusly, one of the major environmental happenings in this century. As one reflects on the fallout problems of the midcentury decade, one cannot but conclude that it was a profound stimulus to the awakening of public awareness to environmental problems. My few remarks here offer scant opportunity to do justice to the story of the first mass public response to a major technological threat to the biosphere. Here too ecologists and other environmental specialists made numerous contributions. Time permits me to do little but hit the highlights of their efforts. First of all it is important to recall that the initial worldwide monitoring of fallout from weapons testing in the early 1950's was a large-scale standardized sampling operation aimed at providing data on the global or continental distribution of fallout. This survey also provided valuable data on gross quantities deposited under more or less standardized conditions.

Recognition that subsequent redistribution of these materials was due to ecological and related physical processes was not long in coming. Many investigators, working in all the major habitats of the globe, began to provide facts, interpretations, and related information on that hitherto little known but most ubiquitous of ecological phenomena - the food chain. Learning about the ecological food chain was one of the greatest mass efforts in public education of all time - but I am not sure that ecologists should be given credit for this achievement. I think that credit for the public's awareness about the movement of ^{90}Sr through the grass-cow-milk-man food chain properly belongs to the various major atomic energy authorities of those countries involved in testing.

What ecologists did contribute was the hard evidence to demonstrate that the fate of certain radionuclides in particular habitats and ecosystems was not predictable, certainly not by any a priori reasoning or usual laboratory data. Ecologists showed that environments differed considerably in how radionuclides would be fixed, altered, moved, or otherwise manipulated. The concept of radionuclide cycling with its attendent phenomena of adsorption vs absorption, bioaccumulation, tropic level transfer with attendent magnification or reduction in concentration, and seasonal variation was enunciated in many ways and by large numbers of environmental scientists. The most immediate contributions of these scientists were the kinds of data which documented the behavior of fallout and demonstrated vividly, as in the case of Arctic ecosystems, that local ecological conditions could profoundly affect the rates and quantities of radionuclides which enter the human diet. The longer-term contribution was the beginning of the establishment of the doctrine that the environment could not be expected to serve as a passive diluent of pollutants. The concomitant of this recognition was acceptance of the need for applying these environmentally derived concepts to all aspects of proposed nuclear technologies.

Another aspect of the weapons testing fallout problem was concern over the possible effects, either short- or long-term, on the environment and its components. Here radioecologists began to confirm what was already derivable from radiobiological laboratory studies, namely, that no recognizable somatic biological effects were likely to be found with the techniques which were then available. Nor have mutations been found that could be attributed to radiation at weapons testing fallout levels.

The problem of low-level effects which might result from chronic exposures to radionuclides derived from weapons testing or radioactive waste releases has also occupied the attention of radioecologists during the past decade and a half. No area of research activity has been fraught with more difficulties in methodology, interpretation, and public and scientific acceptance of results. Radioecologists such as French, Dunaway, Provost, and O'Farrell showed that native small mammal species differed considerably in their radiosensitivity. Their findings have been extremely important in demonstrating that our knowledge of mammalian radiobiology must have a comparative or taxonomic basis in order to provide generality for the findings of laboratory radiobiologists. Similarly in the case of insects, radioecologists such as Crossley, Edwards, Grosch, Reichle, and others have contributed to our understanding of the dose response of insects as affected by life stage, ecological niche, and phylogenetic status.

Perhaps the most important area of low-level effects in terms of contribution of AEC missions relates to the problems of effluents from power reactors and fuel element reprocessing plants. I use the phrase most important in a relative sense. Today the public concern over low-level effects constitutes one of the most important AEC problems. Although low-level effects are associated with the nuclear power plant program, its roots go back to the beginnings of the atomic energy programs. The Hanford Works, site of the first major reactor complex with seven operating reactors originally, also had one of the first teams of radioecologists. Their problems included the effects of waste effluents on Columbia River biota. These ecologists, including Davis, Foster, Nakatani, Watson, Hanson, and others, in both field and laboratory studies provided much data on the lack of response of aquatic organisms to the doses resulting from the Hanford reactor effluents. Their colleagues at the College of Fisheries at the University of Washington, including Donaldson, Held, and others, have contributed to our knowledge of the effects of low doses of ionizing radiation on fishery organisms. In Great Britain, Templeton (now at Hanford), Purdom, Preston, and their colleagues have also helped to bring some light into this murky problem. At Oak Ridge, Blaylock, using the contaminated White Oak Lake as his experimental area, has painstakingly over the past ten years developed a truly unique body of data on the cytogenetic effects of low-level radiation within an environmental context on insects and fish.

The chronic low-level effects problem is one of the most difficult and challenging problems that face environmental scientists. In a forthcoming paper (Auerbach et al. 1971) we recently stated: "Most of the evidence accumulated so far on irradiation effects in actual environments at dose rates less than 1 rad/day is not very convincing. Many authors are quick to qualify their data for positive effects in populations by pointing out that populational and/or environmental factors may have been sufficiently different to cause variations seen between radioactive and nonradioactive areas. To be fair, it also should be admitted that 'negative'data for irradiation effects in populations at very low dose rates far outweigh the 'positive'date. However, a similar criticism might be raised - that is, populational and/or environmental factors in study areas may differ enough to obfuscate subtle irradiation effects which may be present."

What do all these words mean? In somewhat oversimplified terminology they mean that radioecologists have been examining the problem for a long time. They understand the difficulties and the pitfalls lying in the way of obtaining sound objective data, acceptable to the concerned scientific community and the general public, on chronic low-level effects. What radioecologists have not had, however, are the resources to effectively accomplish their task. If this is indeed a priority concern, then I say give us the resources and we will do the job.

Plowshare, the application of nuclear techniques to vast technological projects such as harbor excavation, canal construction, and resource mining, also has been a mission area of the AEC for the last 15 years or so. The proposed use of nuclear explosives for large-scale construction seemed to offer unusual potential for major environmental modifications provided that such projects could be accomplished safely and with minimum biological cost. The first such project to be considered was excavation of a harbor in the Cape Thompson region of Alaska. In 1958 the AEC formed a committee chaired by John Wolfe to develop and recommend a program of bioenvironmental studies to be carried on in Alaska prior to the proposed excavation. These studies were aimed at assessing the biological cost of such an excavation, providing base-line data for subsequent postexcavation evaluations, determining radiation levels and the distribution of radioisotopes in the biota and physical environment in pre- and postdetonation time, and conducting these studies in such a manner that the results would constitute a significant contribution to scientific knowledge. To implement these objectives a team of about 100 scientists was organized to conduct this research - the first major ecological survey ever to be done prior to undertaking a massive technological effort. With all the valid public concern now evident about environmental quality and pollution, it is important to recall for the record the contributions of John Wolfe and other radioecologists and ecologists, both within and without the AEC, who fought for and established the principle that major technological undertakings such as Plowshare must have an ecological assessment prior to their being undertaken. The book "Environment of the Cape Thompson Region, Alaska" (Wilimovsky and Wolfe 1966) is more than the technical report of the scientific investigations carried on in this survey - it really stands as a landmark in our attempts to redress the balance between technological man and environmental man. The wisdom behind and underlying this book is exquisitely distilled in the preface. I commend its reading to each of you.

The next major Plowshare project that provided a basis for ecological contributions was the preexcavation feasibility study for a trans-Isthmian canal to be constructed by nuclear devices. This study, which had to be carried out in part at the proposed sites in Panama and in Columbia, had the specific objective of determining the feasibility of such a project in terms of its radiological hazard to man. With Battelle Memorial Institute, Columbus, acting as the coordinating contractor, teams of radioecologists and other environmental specialists from major AEC installations and from a number of universities undertook the complex task of obtaining the necessary data on human ecology and terrestrial, estuarine, freshwater, and marine ecology, as well as related environmental data, within a short time period, under difficult field conditions, and with limited resources. These field and associated experimental data were then combined into ecological models which, in turn, were used for making estimations of dose to the human populations in the region. The dose assessments which were derived from this preliminary ecological survey and analysis suggested that in terms of somatic dose, reentry into the excavation area may be appropriate eight to ten years after the last detonation. Dose assessments based on genetic dose appeared to be less limiting, suggesting that reentry may be possible within months following the last detonation.

The contributions of ecologists to this project cannot be overemphasized. A key problem in the dose assessment was evaluation of the environmental pathways by which radionuclides could be ingested by human populations. This evaluation, with all its attendent kinetic ecosystem data, was provided by ecologists.

This project then also stands as a landmark study where ecologists and other environmentalists worked with health physicists to assess the safety and hazards of a technological project well before its implementation. Technological assessment is now being recognized as an urgent societal need. I do not think that we have to be bashful in pointing out to all those concerned that ecologists and environmentalists within the radiological community have already pioneered in this area.

Earlier I made mention of power reactor development. The contributions of radioecology have been so considerable that one cannot do justice to the many individuals who have provided, and are continuing to provide, data pertinent to the design, construction, and continuing safe operation of these devices. The speakers who are presenting papers at this Symposium have made their contribution to this mission.

Much of the radioecological effort on radionuclide behavior in the environment has been related to validation of our standards for release of radionuclides. The standards, as we know, have been derived from the permissible levels of radiation exposure to man. It is important to bear in mind that maximum permissible concentrations of radionuclides which may be released to air or water are derived standards whose purpose is to limit the doses to man to acceptable levels. The behavior of specific radionuclides in ecosystems is especially important, because individual radionuclides will behave differently and can be subject to bioaccumulation or reduction within ecological food chains. Not only is it necessary to know the concentration factors of radionuclides in organisms, but it is especially necessary to derive the concentration factors for those food chains or food chain organisms which are likely to provide the greatest degree of human exposure. The collection and assessment of these data, together with associated techniques such as biological monitoring and the development of the specific activity approach for prediction of radionuclide accumulation, have been among the most important contributions that radioecologists have made to the mission programs of the AEC.

During the past 20 years the standards for release of radionuclides to the environment have been continuously under review by boards and committees of the world's most knowledgeable scientists in the general fields of radiation protection. As new data have developed that are pertinent, the standards for release of radionuclides have periodically been made more stringent. There is a high probability that in the immediate future the permissible quantities for release will be reduced again. Each reduction in permissible release poses a responsibility and a need for radioecologists to reevaluate and reexamine the environmental pathways to determine if accumulation of radionuclides is occuring which would lead to excess radiation doses to man.

We are entering a new era of evaluation of nuclear technology within an environmental context. A hitherto not appreciated piece of legislation which will affect the nuclear industry is the Environmental Policy Act of 1969. In many respects this law is the most significant piece of environmental legislation since the Refuse Act of 1899 (33 U.S. Code 407), particularly the section of the law (Section 102) which calls for an evaluation of the potential impact on the environment of any facility constructed by a Federal agency. These environmental impact statements are intended to provide the public sector an opportunity to make an assessment of the environmental impact of any government project. They also provide an opportunity to evaluate the research interests and direction of federal agencies whose missions encompass environmental research and development. All proposed nuclear power plants and all other nuclear facilities will now have to be assessed in the context of this act. Radiological safety and possible ecological damage, as well as consideration of alter alternative modes of accomplishing the same project, are now going to be examined in considerable detail. Radioecologists can anticipate during the next few years that their knowledge and expertise will be needed extensively in the preparation, development, and analysis of environmental impact statements. In addition to providing an ecological evaluation, these statements will also provide an unusual opportunity to identify gaps in our knowledge and to define consequent research needs of the AEC.

The last contribution I wish to mention is the application and refinement of systems analysis techniques to the human exposure problem. Systems analysis and modeling is currently one of the most dynamic fields in ecology. But much of the impetus for this effort began in the field of radioecology, where the need to predict radionuclide transfer within the ecosystem was perceived by radioecologists. The application of compartment model techniques, first worked out by health physicists and biophysicists, to the prediction of radionuclide concentration in particular ecosystem compartments has contributed to AEC program needs and to basic ecology. The radiological hazard assessment of the proposed trans-Isthmian canal could not have been accomplished to the degree of sophistication it attained without the large-scale use of systems methods.

Environmental systems analysis offers considerable potential for helping meet the needs of accurate estimates of radiation doses in a nuclear-powered economy. We believe that the need for a new predictive methodology for human exposure is expected to increase as nuclear power production increases; as air, water, and land are shared at multiple reactor sites; and when power reactors are built more closely together. That the interest in and the importance of this field is growing among radioecologists is attested to by the fact that there are at least ten papers dealing with aspects of environmental systems analysis in this Symposium in contrast with three such papers in the Second National Symposium on Radioecology held just four years ago.

One cannot ignore the contribution to basic ecology. The combination of systems analysis and radioisotope techniques to delineate and quantify ecosystem processes has had a profound impact on that part of ecology dealing with ecosystem analysis. Not only the techniques themselves but the insights, understandings, and ideas derived from the application of these radioecological concepts have served to stimulate wide interest in ecosystem analysis and have provided new insights into the structure and functioning of ecosystems.

In my opening remarks I pointed out that it was pertinent to view radioecology in an axiological context. I stated that it is timely to view the contributions of radioecology in terms of their value to society, to science, and to the AEC. In an earlier essay Weinberg (1964) outlined a set of criteria by which one can rate scientific fields - not in a philosophical but in a practical sense. In this axiology Weinberg proposed two different kinds of criteria: internal and external. The internal criteria arise from within the science itself; the external criteria stem from the social or other settings in which the science is embedded. I believe that it is appropriate to consider radioecology in terms of the three external criteria of Weinberg - namely, technological merit, social merit, and scientific merit. Scientific merit is measured by the degree to which a field of science contributes to and illuminates the neighboring fields in which it is embedded. The previous speaker, Dr. Odum, has outlined the contributions that radioecology has made to our understanding of ecosystems, and I have briefly reinforced his points.

Social merit means the degree to which a scientific activity contributes to achievement of a social goal. If the development of a safe, clean, cheaper, and unlimited energy source is a social goal, then I submit that its attainment will be extremely difficult without the contributions of radioecology.

Technological merit means the degree to which a scientific activity contributes to achievement of a technological aim. Power reactors reflect the consummate knowledge and skill of physicists, engineers, chemists, and others. But unless power reactors can be demonstrated to be irrevocably safe in their operation, those aforementioned accomplishment will be for naught. Radic ecology, among other related disciplines, is required to make sure that the technological objective of safety is attained and that environmental impact is minimal.

If you add up the contributions of radioecology to the mission programs of the AEC and subject these contributions to the axiological criteria I have enumerated, you can come to only one conclusion - that radioecology has been and still is grossly undervalued.

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PART II. RADIONUCLIDE CYCLING

Preface

Behavior of radionuclides in the environment is governed by a highly complex set of natural processes and circumstances. Nearly every component of an ecological system will have some influence upon the fate of radioactive materials introduced into the system. Of major significance, however, is the fact that natural processes may concentrate radionuclides in biological tissues to levels that are orders of magnitude higher than in the universal media air and water. Further, there is no doubt that radionuclides, in sufficient concentrations, are harmful to all living systems.

Questions to be asked regarding concentration of radionuclides in ecological systems include for example: How rapidly do radionuclides move from one part of a system to another and what are the mechanisms and pathways which allow such transfers? What are the concentrations and radiation doses from radionuclides in important biological species relative to the total amount of environmental contamination? What is the long-term behavior of radionuclides in the environment?

Research into these questions gives information useful not only to people concerned with radiation hazards, but also to those concerned with other forms of pollution and to those studying normal functions of ecological systems. Relative ease of measurement of minute amounts of radioactivity has helped make radionuclides a "model pollutant". Ecological processes which govern radionuclide behavior also affect behavior of smog, pesticides and other chemical substances which threaten the environment. Since the ecosystem itself largely regulates the movement and concentration of radionuclides, observation of radionuclide behavior can, in conjunction with suitable models, yield basic information about the functional processes within the system.

References listed in Part II pertain to the movement and concentration of radionuclides in marine, freshwater and terrestrial ecosystems. Natural ecosystems as opposed to agricultural systems have received the major emphasis. The various works given reference have taken several approaches, including theoretical, experimental or observational ones. In our opinion, a synthesis of all three approaches is necessary to yield maximum insight into the problems of radionuclide concentration.

Toxic Substances and Ecological Cycles

Radioactive elements or pesticides such as DDT that are released in the environment may enter meteorological and biological cycles that distribute them and can concentrate them to dangerous levels

by George M. Woodwell

The vastness of the earth has fostered a tradition of unconcern about the release of toxic wastes into the environment. Billowing clouds of smoke are diluted to apparent nothingness; discarded chemicals are flushed away in rivers; insecticides "disappear" after they have done their job; even the massive quantities of radioactive debris of nuclear explosions are diluted in the apparently infinite volume of the environment. Such pollutants are indeed diluted to traces—to levels infinitesimal by ordinary standards, measured as parts per billion or less in air, soil and water. Some pollutants do disappear; they are immobilized or decay to harmless substances. Others last, sometimes in toxic form, for long periods. We have learned in recent years that dilution of persistent pollutants even to trace levels detectable only by refined techniques is no guarantee of safety. Nature has ways of concentrating substances that are frequently surprising and occasionally disastrous.

We have had dramatic examples of one of the hazards in the dense smogs that blanket our cities with increasing frequency. What is less widely realized is that there are global, long-term ecological processes that concentrate toxic substances, sometimes hundreds of thousands of times above levels in the environment. These processes include not only patterns of air and water circulation but also a complex series of biological mechanisms. Over the past decade detailed studies of the distribution of both radioactive debris and pesticides have revealed patterns that have surprised even biologists long familiar with the unpredictability of nature.

Major contributions to knowledge of these patterns have come from studies of radioactive fallout. The incident that triggered worldwide interest in large-scale radioactive pollution was the hydrogen-bomb test at Bikini in 1954 known as "Project Bravo." This was the test that inadvertently dropped radioactive fallout on several Pacific islands and on the Japanese fishing vessel *Lucky Dragon*. Several thousand square miles of the Pacific were contaminated with fallout radiation that would have been lethal to man. Japanese and U.S. oceanographic vessels surveying the region found that the radioactive debris had been spread by wind and water, and, more disturbing, it was being passed rapidly along food chains from small plants to small marine organisms that ate them to larger animals (including the tuna, a staple of the Japanese diet).

The U.S. Atomic Energy Commission and agencies of other nations, particularly Britain and the U.S.S.R., mounted a large international research program, costing many millions of dollars, to learn the details of the movement of such debris over the earth and to explore its hazards. Although these studies have been focused primarily on radioactive materials, they have produced a great deal of basic information about pollutants in general. The radioactive substances serve as tracers to show the transport and concentration of materials by wind and water and the biological mechanisms that are characteristic of natural communities.

One series of investigations traced the worldwide movement of particles in the air. The tracer in this case was strontium 90, a fission product released into the earth's atmosphere in large quantities by nuclear-bomb tests. Two reports in 1962 —one by S. Laurence Kulp and Arthur R. Schulert of Columbia University and the other by a United Nations committee—furnished a detailed picture of the travels of strontium 90. The isotope was concentrated on the ground between the latitudes of 30 and 60 degrees in both hemispheres, but concentrations were five to 10 times greater in the Northern Hemisphere, where most of the bomb tests were conducted.

It is apparently in the middle latitudes

FOREST COMMUNITY is an integrated array of plants and animals that accumulates and reuses nutrients in stable cycles, as indicated schematically in black. DDT participates in parallel cycles (*color*). The author measured DDT residues in a New Brunswick forest in which four pounds per acre of DDT had been applied over seven years. (Studies have shown about half of this landed in the forest, the remainder dispersing in the atmosphere.) Three years after the spraying, residues of DDT were as shown (in pounds per acre).

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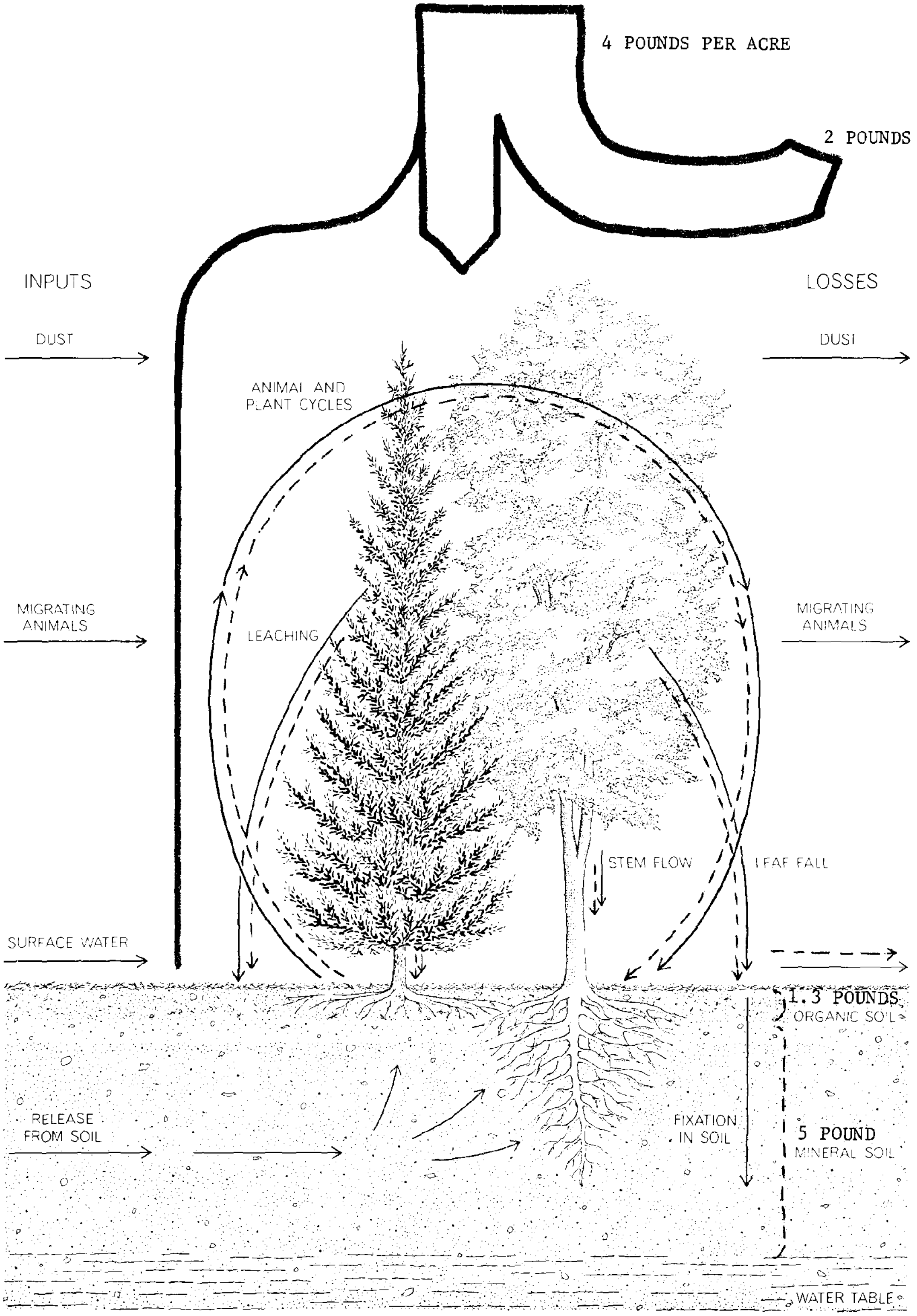

4 POUNDS PER ACRE
2 POUNDS
INPUTS
LOSSES
DUST
DUST
ANIMAL AND PLANT CYCLES
MIGRATING ANIMALS
LEACHING
MIGRATING ANIMALS
STEM FLOW
LEAF FALL
SURFACE WATER
1.3 POUNDS
ORGANIC SOIL
RELEASE FROM SOIL
FIXATION IN SOIL
5 POUND
MINERAL SOIL
WATER TABLE

that exchanges occur between the air of upper elevations (the stratosphere) and that of lower elevations (the troposphere). The larger tests have injected debris into the stratosphere; there it remains for relatively long periods, being carried back into the troposphere and to the ground in the middle latitudes in late winter or spring. The mean "half-time" of the particles' residence in the stratosphere (that is, the time for half of a given injection to fall out) is from three months to five years, depending on many factors, including the height of the injection, the size of the particles, the latitude of injection and the time of year. Debris injected into the troposphere has a mean half-time of residence ranging from a few days to about a month. Once airborne, the particles may travel rapidly and far. The time for one circuit around the earth in the middle latitudes varies from 25 days to less than 15. (Following two recent bomb tests in China fallout was detected at the Brookhaven National Laboratory on Long Island respectively nine and 14 days after the tests.)

Numerous studies have shown further that precipitation (rain and snowfall) plays an important role in determining where fallout will be deposited. Lyle T. Alexander of the Soil Conservation Service and Edward P. Hardy, Jr., of the AEC found in an extensive study in Clallam County, Washington, that the amount of fallout was directly proportional to the total annual rainfall.

It is reasonable to assume that the findings about the movement and fallout of radioactive debris also apply to other particles of similar size in the air. This conclusion is supported by a recent report by Donald F. Gatz and A. Nelson Dingle of the University of Michigan, who showed that the concentration of pollen in precipitation follows the same pattern as that of radioactive fallout. This observation is particularly meaningful because pollen is not injected into the troposphere by a nuclear explosion; it is picked up in air currents from plants close to the ground. There is little question that dust and other particles, including small crystals of pesticides, also follow these patterns.

From these and other studies it is clear that various substances released into the air are carried widely around the world and may be deposited in concentrated form far from the original source. Similarly, most bodies of water—especially the oceans—have surface currents that may move materials five to 10 miles a day. Much higher rates, of course, are found in such major oceanic currents as the Gulf Stream. These currents are one more physical mechanism that can distribute pollutants widely over the earth.

The research programs of the AEC and other organizations have explored not only the pathways of air and water transport but also the pathways along which pollutants are distributed in plant and animal communities. In this connection we must examine what we mean by a "community."

Biologists define communities broadly to include all species, not just man. A natural community is an aggregation of a great many different kinds of organisms, all mutually interdependent. The basic conditions for the integration of a community are determined by physical characteristics of the environment such as climate and soil. Thus a sand dune supports one kind of community, a freshwater lake another, a high mountain still another. Within each type of environment there develops a complex of organisms that in the course of evolution becomes a balanced, self-sustaining biological system.

Such a system has a structure of interrelations that endows the entire community with a predictable developmental pattern, called "succession," that leads toward stability and enables the community to make the best use of its physical environment. This entails the development of cycles through which the community as a whole shares certain resources, such as mineral nutrients and energy. For example, there are a number of different inputs of nutrient elements into such a system. The principal input is from the decay of primary minerals in the soil. There are also certain losses, mainly through the leaching of substances into the underlying water table. Ecologists view the cycles in the system as mechanisms that have evolved to conserve the elements essential for the survival of the organisms making up the community.

One of the most important of these cycles is the movement of nutrients and energy from one organism to another along the pathways that are sometimes called food chains. Such chains start with plants, which use the sun's energy to synthesize organic matter; animals eat the plants; other animals eat these herbivores, and carnivores in turn may constitute additional levels feeding on the herbivores and on one another. If the lower orders in the chain are to survive and endure, there must be a feedback of nutrients. This is provided by decay organisms (mainly microorganisms) that break down organic debris into the substances used by plants. It is also obvious that the community will not survive if essential links in the chain are eliminated; therefore the preying of one level on another must be limited.

Ecologists estimate that such a food chain allows the transmission of roughly 10 percent of the energy entering one level to the next level above it, that is, each level can pass on 10 percent of the energy it receives from below without suffering a loss of population that would imperil its survival. The simplest version of a system of this kind takes the form of a pyramid, each successively higher population receiving about a tenth of the energy received at the level below it.

Actually nature seldom builds communities with so simple a structure. Almost invariably the energy is not passed along in a neatly ordered chain but is spread about to a great variety of organisms through a sprawling, complex web of pathways [*see illustration on preceding two pages*]. The more mature the community, the more diverse its makeup and the more complicated its web. In a natural ecosystem the network may consist of thousands of pathways.

This complexity is one of the principal factors we must consider in investigating how toxic substances may be distributed and concentrated in living communities. Other important basic factors lie in the nature of the metabolic process. For example, of the energy a population of organisms receives as food, usually less than 50 percent goes into the construction of new tissue, the rest being spent for respiration. This circumstance acts as a concentrating mechanism: a substance not involved in respiration and not excreted efficiently may be concentrated in the tissues twofold or more when passed from one population to another.

Let us consider three types of pathway for toxic substances that involve man as the ultimate consumer. The three examples, based on studies of radioactive substances, illustrate the complexity and variety of pollution problems.

The first and simplest case is that of strontium 90. Similar to calcium in chemical behavior, this element is concentrated in bone. It is a long-lived radioactive isotope and is a hazard because its energetic beta radiation can damage the mechanisms involved in the manufacture of blood cells in the bone marrow. In the long run the irradiation may produce certain types of cancer. The route of strontium 90 from air to man is rather direct: we ingest it in leafy vegetables, which absorbed it from the soil or received it as fallout from the air, or in milk and other dairy products from cows that have fed on contaminated vegetation. Fortunately strontium is not usually concentrated in man's food by an extensive food chain. Since it lodges chiefly in bone, it is not concentrated in passing from animal to animal in the same ways other radioactive substances may be (unless the predator eats bones!).

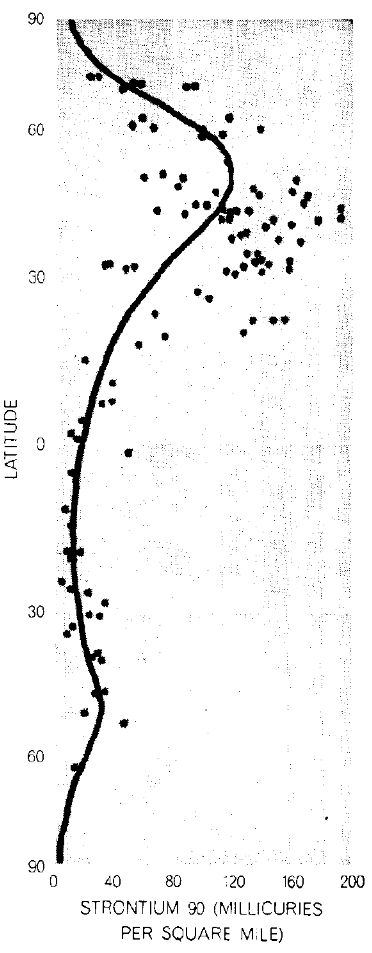
Quite different is the case of the radioactive isotope cesium 137. This isotope, also a fission product, has a long-lived radioactivity (its half-life is about 30 years) and emits penetrating gamma rays. Because it behaves chemically like potassium, an essential constituent of all cells, it becomes widely distributed once it enters the body. Consequently it is passed along to meat-eating animals, and under certain circumstances it can accumulate in a chain of carnivores.

A study in Alaska by Wayne C. Hanson, H. E. Palmer and B. I. Griffin of the AEC's Pacific-Northwest Laboratory showed that the concentration factor for cesium 137 may be two or three for one step in a food chain. The first link of the chain in this case was lichens growing in the Alaskan forest and tundra. The lichens collected cesium 137 from fallout in rain. Certain caribou in Alaska live mainly on lichens during the winter, and caribou meat in turn is the principal diet of Eskimos in the same areas. The investigators found that caribou had accumulated about 15 micromicrocuries of cesium radioactivity per gram of tissue in their bodies. The Eskimos who fed on these caribou had a concentration twice as high (about 30 micromicrocuries per gram of tissue) after eating many pounds of caribou meat in the course of a season. Wolves and foxes that ate caribou sometimes contained three times the concentration in the flesh of the caribou. It is easy to see that in a longer chain, involving not just two animals but several, the concentration of a substance that was not excreted or metabolized could be increased to high levels.

A third case is that of iodine 131, another gamma ray emitter. Again the chain to man is short and simple: The contaminant (from fallout) comes to man mainly through cows' milk, and thus the chain involves only grass, cattle, milk and man. The danger of iodine 131 lies in the fact that iodine is concentrated in the thyroid gland. Although iodine 131 is short-lived (its half-life is only about eight days), its quick and localized concentration in the thyroid can cause damage. For instance, a research team from the Brookhaven National Laboratory headed by Robert Conard has discovered that children on Rongelap Atoll who were exposed to fallout from the 1954 bomb test later developed thyroid nodules.

FALLOUT is distributed around the earth by meteorological processes. Deposits of strontium 90, for instance, are concentrated between 30 and 60 degrees north, as shown by depth of color on the map and by the curve (*right*). Points on the chart represent individual samples. The data are from a study made in 1963 and 1964 by Robert J. List and colleagues in several U.S. agencies. Such studies have not been made for pesticides but it appears that DDT may also be carried in air and deposited in precipitation.

(map not reproduced)



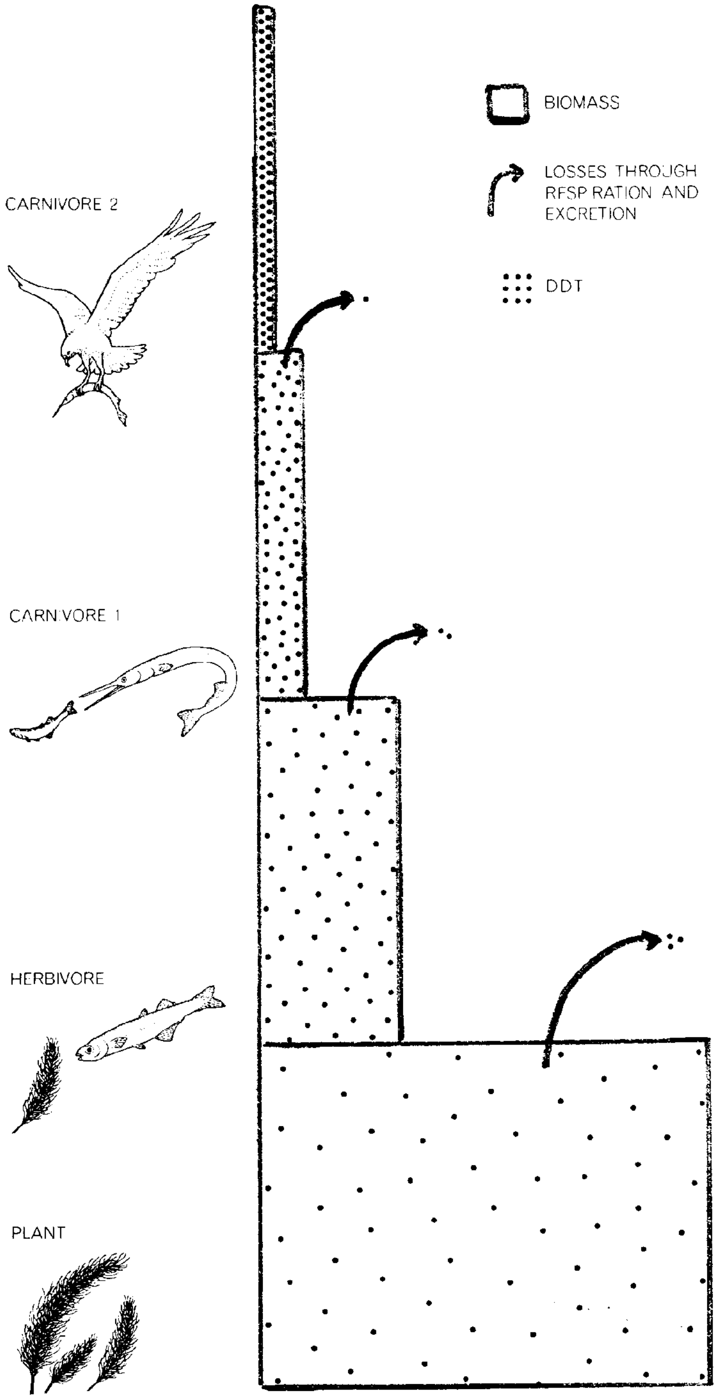
The investigations of the iodine 131 hazard yielded two lessons that have an important bearing on the problem of pesticides and other toxic substances released in the environment. In the first place we have had a demonstration that the hazard of the toxic substance itself often tends to be underestimated. This was shown to be true of the exposure of the thyroid to radiation. Thyroid tumors were found in children who had been treated years before for enlarged thymus glands with doses of X rays that had been considered safe. As a result of this discovery and studies of the effects of iodine 131, the Federal Radiation Council in 1961 issued a new guide reducing the permissible limit of exposure to ionizing radiation to less than a tenth of what had previously been accepted. Not the least significant aspect of this lesson is the fact that the toxic effects of such a hazard may not appear until long after the exposure; on Rongelap Atoll 10 years passed before the thyroid abnormalities showed up in the children who had been exposed.

The second lesson is that, even when the pathways are well understood, it is almost impossible to predict just where toxic substances released into the environment will reach dangerous levels. Even in the case of the simple pathway followed by iodine 131 the eventual destination of the substance and its effects on people are complicated by a great many variables: the area of the cow's pasture (the smaller the area, the less fallout the cow will pick up); the amount and timing of rains on the pasture (which on the one hand may bring down fallout but on the other may wash it off the forage); the extent to which the cow is given stored, uncontaminated feed; the amount of iodine the cow secretes in its milk; the amount of milk in the diet of the individual consumer, and so on.

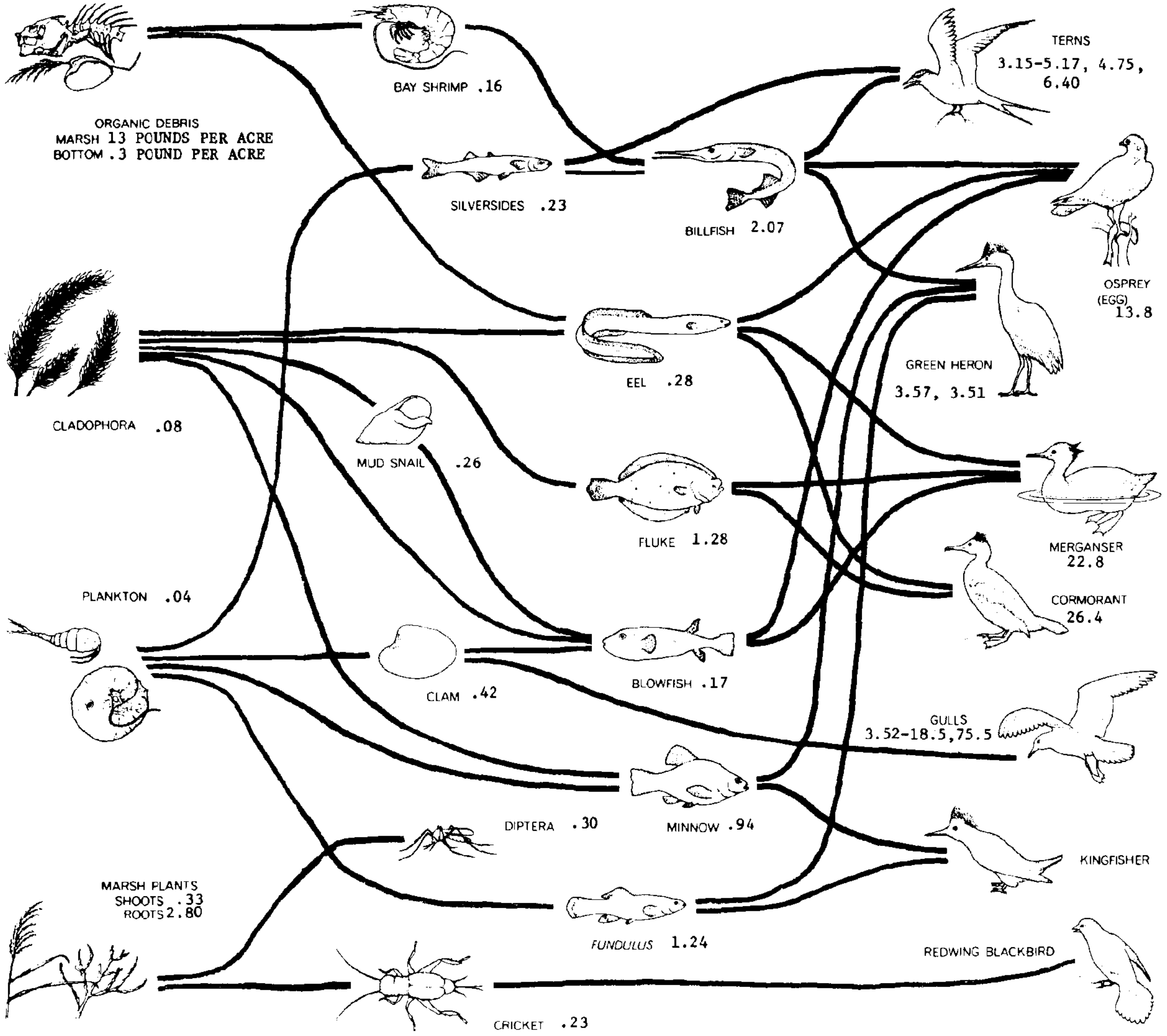
If it is difficult to estimate the nature and extent of the hazards from radioactive fallout, which have been investigated in great detail for more than a decade by an international research program, it must be said that we are in a poor position indeed to estimate the hazards from pesticides. So far the amount of research effort given to the ecological effects of these poisons has been comparatively small, although it is increasing rapidly. Much has been learned, however, about the movement and distribution of pesticides in the environment, thanks in part to the clues supplied by the studies of radioactive fallout.

Our chief tool in the pesticide inquiry is DDT. There are many reasons for focusing on DDT: it is long-lasting, it is now comparatively easy to detect, it is by far the most widely used pesticide and it is toxic to a broad spectrum of animals, including man. Introduced only a quarter-century ago and spectacularly successful during World War II in controlling body lice and therefore typhus, DDT quickly became a universal weapon in agriculture and in public health campaigns against disease-carriers. Not surprisingly, by this time DDT has thoroughly permeated our environment. It is found in the air of cities, in wildlife all over North America and in remote corners of the earth, even in Adélie penguins and skua gulls (both carnivores) in the Antarctic. It is also found the world over in the fatty tissue of man. It is fair to say that there are probably few populations in the world that are not contaminated to some extent with DDT.

We now have a considerable amount of evidence that DDT is spread over the earth by wind and water in much the same patterns as radioactive fallout. This seems to be true in spite of the fact that DDT is not injected high into the atmosphere by an explosion. When DDT is sprayed in the air, some fraction of it is picked up by air currents as pollen is, circulated through the lower troposphere and deposited on the ground by rainfall. I found in tests in Maine and New Brunswick, where DDT has been sprayed from airplanes to control the spruce budworm in forests, that even in the open, away from trees, about 50 percent of the DDT does not fall to the ground. Instead it is probably dispersed as small crystals in the air. This is true even on days when the air is still and when the low-flying planes release the spray only 50 to 100 feet above treetop level. Other mechanisms besides air movement can carry DDT for great distances around the world. Migrating fish and birds can transport it thousands of miles. So also do oceanic currents. DDT has only a low solubility in water (the upper limit is about one part per billion), but as algae and other organisms in the water absorb the substance in fats, where it is highly soluble, they make room for more DDT to be dissolved into the water. Ac-



CONCENTRATION of DDT residues being passed along a simple food chain is indicated schematically in this diagram. As "biomass," or living material, is transferred from one link to another along such a chain, usually more than half of it is consumed in respiration or is excreted (*arrows*); the remainder forms new biomass. The losses of DDT residues along the chain, on the other hand, are small in proportion to the amount that is transferred from one link to the next. For this reason high concentrations occur in the carnivores.



FOOD WEB is a complex network through which energy passes from plants to herbivores and on to carnivores within a biological community. This web showing some of the plants and animals in a Long Island estuary and along the nearby shore was developed by Dennis Puleston of the Brookhaven National Laboratory. Numbers indicate residues of DDT and its derivatives (in parts per million, wet weight, whole-body basis) found in the course of a study made by the author with Charles F. Wurster, Jr., and Peter A. Isaacson.

cordingly water that never contains more than a trace of DDT can continuously transfer it from deposits on the bottom to organisms.

LOCATION		ORGANISM	TISSUE	CONCENTRATION (PARTS PER MILLION)
U.S. (AVERAGE)		MAN	FAT	11
ALASKA (ESKIMO)				2.8
ENGLAND				2.2
WEST GERMANY				2.3
FRANCE				5.2
CANADA				5.3
HUNGARY				12.4
ISRAEL				19.2
INDIA				12.8-31.0
U.S.	CALIFORNIA	PLANKTON		5.3
	CALIFORNIA	BASS	EDIBLE FLESH	4-138
	CALIFORNIA	GREBES	VISCERAL FAT	UP TO 1,600
	MONTANA	ROBIN	WHOLE BODY	6.8-13.9
	WISCONSIN	CRUSTACEA		.41
	WISCONSIN	CHUB	WHOLE BODY	4.52
	WISCONSIN	GULL	BRAIN	20.8
	MISSOURI	BALD EAGLE	EGGS	1.1-5.6
	CONNECTICUT	OSPREY	EGGS	6.5
	FLORIDA	DOLPHIN	BLUBBER	ABOUT 220
CANADA		WOODCOCK	WHOLE BODY	1.7
ANTARCTICA		PENGUIN	FAT	.015-.18
ANTARCTICA		SEAL	FAT	.042-.12
SCOTLAND		EAGLE	EGGS	1.18
NEW ZEALAND		TROUT	WHOLE BODY	.6-.8

DDT RESIDUES, which include the derivatives DDD and DDE as well as DDT itself, have apparently entered most food webs. These data were selected from hundreds of reports that show DDT has a worldwide distribution, with the highest concentrations in carnivorous birds.

DDT is an extremely stable compound that breaks down very slowly in the environment. Hence with repeated spraying the residues in the soil or water basins accumulate. Working with Frederic T. Martin of the University of Maine, I found that in a New Brunswick forest where spraying had been discontinued in 1958 the DDT content of the soil increased from half a pound per acre to 1.8 pounds per acre in the three years between 1958 and 1961. Apparently the DDT residues were carried to the ground very slowly on foliage and decayed very little. The conclusion is that DDT has a long half-life in the trees and soil of a forest, certainly in the range of tens of years.

Doubtless there are many places in the world where reservoirs of DDT are accumulating. With my colleagues Charles F. Wurster, Jr., and Peter A. Isaacson of the State University of New York at Stony Brook, I recently sampled a marsh along the south shore of Long Island that had been sprayed with DDT for 20 years to control mosquitoes. We found that the DDT residues in the upper layer of mud in this marsh ranged up to 32 pounds per acre!

We learned further that plant and animal life in the area constituted a chain that concentrated the DDT in spectacular fashion. At the lowest level the plankton in the water contained .04 part per million of DDT; minnows contained one part per million, and a carnivorous scavenging bird (a ring-billed gull) contained about 75 parts per million in its tissues (on a whole-body, wet-weight basis). Some of the carnivorous animals in this community had concentrated DDT by a factor of more than 1,000 over the organisms at the base of the ladder.

A further tenfold increase in the concentrations along this food web would in all likelihood result in the death of many of the organisms in it. It would then be impossible to discover why they had disappeared. The damage from DDT concentration is particularly serious in the higher carnivores. The mere fact that conspicuous mortality is not observed is no assurance of safety. Comparatively low concentrations may inhibit reproduction and thus cause the species to fade away.

That DDT is a serious ecological hazard was recognized from the beginning of its use. In 1946 Clarence Cottam and Elmer Higgins of the U.S. Fish and Wildlife Service warned in the *Journal of Economic Entomology* that the pesticide was a potential menace to mammals, birds, fishes and other wildlife and that special care should be taken to avoid its application to streams, lakes and coastal bays because of the sensitivity of fishes and crabs. Because of the wide distribution of DDT the effects of the substance on a species of animal can be more damaging than hunting or the elimination of a habitat (through an operation such as dredging marshes). DDT affects the entire species rather than a single population and may well wipe out the species by eliminating reproduction.

Within the past five years, with the development of improved techniques for detecting the presence of pesticide residues in animals and the environment, ecologists have been able to measure the extent of the hazards presented by DDT and other persistent general poisons. The picture that is emerging is not a comforting one. Pesticide residues have now accumulated to levels that are catastrophic for certain animal populations, particularly carnivorous birds. Furthermore, it has been clear for many years that because of their shotgun effect these weapons not only attack the pests but also destroy predators and competitors that normally tend to limit proliferation of the pests. Under exposure to pesticides the pests tend to develop new strains that are resistant to the chemicals. The result is an escalating chemical warfare that is self-defeating and has secondary effects whose costs are only beginning to be measured. One of the costs is wildlife, notably carnivorous and scavenging birds such as hawks and eagles. There are others: destruction of food webs aggravates pollution problems, particularly in bodies of water that receive mineral nutrients in sewage or in water draining from heavily fertilized agricultural lands. The plant populations, no longer consumed by animals, fall to the bottom to decay anaerobically, producing hydrogen sulfide and other noxious gases, further degrading the environment.

The accumulation of persistent toxic substances in the ecological cycles of the earth is a problem to which mankind will have to pay increasing attention. It affects many elements of society, not only in the necessity for concern about the disposal of wastes but also in the need for a revolution in pest control. We must learn to use pesticides that have a short half-life in the environment—better yet, to use pest-control techniques that do not require applications of general poisons. What has been learned about the dangers in polluting ecological cycles is ample proof that there is no longer safety in the vastness of the earth.

Turnover and Concentration of Radionuclides in Food Chains

By D. E. Reichle, P. B. Dunaway, and D. J. Nelson

Abstract: *Proliferation of nuclear technology and concern for radioactivity in the biosphere demand more sophisticated evaluations of future nuclear installations and procedures. Adequate analyses of radionuclide dispersion in the environment will require more substantial bioenvironmental information than is presently available. Frequently information known for one ecological system (e.g., arctic tundra) will not be applicable to other ecosystems (e.g., temperate or tropical forests). Only with sufficient ecological data can predictive models be developed that will enable assessment of the environmental consequences of radioactive contamination. A simple source–pathway–receptor model, analogous to the ecological food chain, requires pathway identification, data on assimilation by each link (organism) in the pathway, and determination of the biological turnover of each radionuclide. For acute releases of radioactivity to the environment, evaluation of these variables is needed to predict time-dependent concentrations of radioactivity in organisms. For chronic releases, concentration factors alone will often suffice. The biological concentration and turnover of radionuclides by animals are summarized in this paper. Data are presented for use in environmental models and correlation with species*

Reichle, D. E., P. B. Dunaway and D. J. Nelson. 1970. Turnover and concentration of radionuclides in food chains. Nuclear Safety 11(1):43-55.

characteristics (e.g., body size) that allow estimation of absolute values for many different animal groups based on existing experimental data.

The intensified technological development of atomic energy in the last decade has added a new dimension to the problems associated with maintaining environmental quality. Considerable research effort has therefore been devoted to studying the fate and potential hazards of radionuclides released to the environment by man. The modes of environmental contamination with radionuclides may be either acute or chronic as a result of the intentional or unintentional consequences of man's activities; for example, global fallout from nuclear weapons testing,[1] accidental industrial releases,[2] neutron-activation products and waste-disposal operations of nuclear industry,[3,4] and special applications, such as the proposed nuclear excavation of a transisthmian sea-level canal.[5] Analyses of the environmental behavior of radionuclides and their potential danger to human populations have consistently emphasized five sequential steps in the development of environmental models:

1. Determination of quantity and distribution of radionuclides produced.
2. Identification of nuclides.
3. Investigation of bioenvironmental pathways and processes (biogeochemical cycles).
4. Evaluation of doses to man from internal and external sources.
5. Consideration of protective action.

Approximately 200 isotopes of some 35 different elements have been identified from nuclear explosions and fallout.[6] Because of yield, half-life, and biological characteristics, 13 radionuclides are likely to be of importance in the proposed transisthmian canal.[5] Included in these are ^{90}Sr, ^{131}I, ^{137}Cs, and ^{3}H, which we consider to be of ecological interest in connection with reactor waste releases. Considerable information is available about environmental behavior of ^{90}Sr, ^{131}I, and ^{137}Cs. Some critics of nuclear power have identified tritium as potentially a critical radionuclide in some biological systems. The most recent review of tritium does not include bioenvironmental information.[7] Similarly, although much more is known about the ecological behavior of certain other elements, there are still insufficient data on many food chains for development of meaningful models of radionuclide transport.[8] Currently there is growing concern about the quality of our environment and its biological constituents. This concern coupled with the relative paucity of research in some areas of environmental biology has resulted in the establishment of several new research activities in these areas. However, controlled releases of radioactive materials into the general environment up to the present time have been restricted to such low levels that the health and safety of the public apparently are adequately protected.

The study of uptake and turnover of radionuclides by means of the biological processes occurring in organisms has been undertaken to develop a tool for assessing the ecological consequences of radioactivity in nature. In this paper we deal with this part of the overall problem and illustrate how the contrasting biological composition and ecological processes of different food chains may affect the significant modification of radionuclide concentrations from the source to man. Comparisons of the biological half-lives of radionuclides in different animal species from invertebrates to man illustrate the variable retention times of each isotope among dissimilar species and different isotopes within the same species. Other data are presented to show the different concentration factors of elements by animals from their food bases. Knowledge of the values of these parameters can form the basis of predictive models for nuclear safety in the environment. The data cited in this summary for invertebrates, fish, and mammals were summarized from several hundred publications. Since it was not feasible to include all these literature sources in this report, they were documented in Ref. 9.

Concentration Factors

There are many factors that determine the food-chain concentration of radionuclides by animals. The most important is the stable-element chemistry of the organism, which in turn can be affected by a number of physiological and ecological conditions. The specific-activity concept[10] is one technique that permits a priori prediction of the steady-state distribution of radionuclides released to the environment. Specific activity is defined as the ratio of radioactive atoms to total atoms of the same element. By using the stable-element distribution in environmental samples as a chemical analog for the radionuclide, we can predict the dispersion of long-lived radionuclides through environmental pathways if we know: (1) the stable-element chemistry of organisms constituting the links in the biological pathways (food chains) and (2) the specific-activity ratio of the element at the source of its access to the food chain,

$$\frac{\text{Radionuclide in food}}{\text{Total element in food}} = \frac{\text{radionuclide in consumer}}{\text{total element in consumer}} \quad (1)$$

This ratio is valid only if there is complete environmental mixing and no biological discrimination between the radionuclide and its stable-isotope analog. The ratio can be used only if adequate knowledge is available for the chemistry of the ecological system.

The food-chain kinetics and distribution of elements and their radionuclides are dependent on a number of environmental and biological factors; for example, geochemical characteristics of the ecosystem, dietary levels of nutrients in foodstuffs, and the physiological demands of consumer organisms. Consequently it is difficult to draw specific conclusions concerning the biological concentration of elements in different ecosystems. The primary ecological mechanism for interorganism transport of elements is the food chain.

Concentrations in Food Chains

Functionally, terrestrial food chains may be delimited into trophic levels (or successive links in the feeding process). Limited data on the concentration of stable elements are available for some food chains (Table 1). These data are presented as concentration factors (ratio of element level in consumer to element level in food-chain base) for each trophic level, with base values normalized at 1.0. These ratios are taken from either stable-element chemical analyses of food-chain components or, under conditions of chronic environmental contamination, equilibrium values of radionuclides along food chains.[9] Calcium and strontium show the greatest reduction in whole-body concentrations in insects and other invertebrates (a factor of ~0.1 for second-order consumers and predators), although these data do not include species with calcified exoskeletons. Calcium and strontium may be concentrated by factors greater than 150 in "calcium-sink" invertebrates, such as millipedes, isopods, and snails.[11] In vertebrates, other bone-seeking radionuclides (e.g., ^{187}W) might presumably display the same distinctive behavior as do calcium and strontium in these invertebrates. Cobalt, potassium, and cesium progressively decrease in concentration through invertebrate food chains, with element contents generally averaging one-half those of plants after two trophic exchanges.[12] Phosphorus levels in insects may be 10-fold greater than those of their detritus or foliage food bases, although little subsequent change occurs between animal components of the food chain. Sodium is continually concentrated at each trophic level, and indirect evidence presently indicates that this element may be limiting in terrestrial detritus-based food chains.

Concentration factors for mammals were derived from fallout studies in arctic, desert, and temperate-zone ecosystems or from laboratory studies where the radioactivity of chronically fed food and equilibrium levels of the animals were known. Concentration factors of most elements for which we have information decrease from plants to mammalian herbivores. Cesium concentrations increase at the higher trophic levels in mammals, in contrast to the concentrations of this alkali metal in terrestrial invertebrates. Ninefold increases of ^{137}Cs through plant–mule deer–cougar food chains have been reported,[13] as have increases by about a factor of 2 at each successive link of the lichen–caribou–wolf chain[14] and an increase by a factor of 3 in humans over that of their food.[15] Uptake of some elements in herbivores is apparently affected by the type or form of vegetation available to the animals.[16] Considerable diversity of radionuclide concentrations in mammalian omnivores and carnivores should be expected because of varied feeding habits, such as seasonal changes in diet and selective feeding on tissues.

Concentration in Aquatic Systems

The concentration of elements in aquatic ecosystems (Table 1) is highly variable.[17] Of major importance in affecting the mineral nutrition of aquatic food chains is the chemical composition of the water. Nutrient-poor (oligotrophic) systems generally require the greatest concentration of elements to levels necessary for the life processes. In eutrophic waters (nutrient-rich but not necessarily available) concentration factors of nutrients by organisms are not as great. Concentration factors are usually related to the chemical content of the media, and it is impossible to predict or draw conclusions from the elemental composition of organisms without simultaneous reference data on their water–food environment.[18] Since many aquatic organisms may take up elements directly from water, as well as by food ingestion, water is used as the reference base here instead of plants.

In aquatic ecosystems, strontium and manganese are accumulated in the shells of clams and snails. Phosphorus may be concentrated to very high levels by both vertebrates and invertebrates. Cesium and potassium concentrations in aquatic animals are higher than in water but generally show little or no increase from plant to herbivore to predator, although the cesium-to-

Table 1 Aquatic and Terrestrial Food-Chain Concentration of Elements*

Trophic level†		Element concentration factors‡													
		Ca	Sr	K	Cs	Na	Co	Zn	Mn	Ru	Fe	H	P	Ra	I
Aquatic															
Water		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Algae and higher plants		1–400	10–3000		50–25,000		2500–6200	140–33,500	700–35,000	80–2000	2400–200,000		36,000–50,000	0.5	60–200
Invertebrates	S	16	10–4000		60–11,000		325		6000–140,000	130			2–100,000	0.5	20–1000
	H		1		600			150			125		2000		
	C				800										
Fish	O		1	300–2500	125–6000						10,000		3000–100,000	0.5	25–50
	C	0.5–300	1–150	400–2700	640–9500			4–40						1.5	
Terrestrial															
Plants		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Invertebrates	S	0.1–18		3.5	0.2	17						0.6	11		
	H	0.1	0.1	3.0	0.3–0.5	21	0.4			0.4			17		
	C	0.1	0.1	2.0	0.1–0.5	27	0.5			1.2			18		
Mammals	H		0.5–4.5		0.3–2.0		0.3			0.4	0.8	0.6		0.01	0.5
	O				1.2–2.0						0.2				0.2
	C				3.8–7.0										0.1

*Data summarized from Ref. 9.

†S = saprovore (detritus-feeder); H = herbivore; C = carnivore; O = omnivore.

‡Ratio of element level in consumer to element level in food-chain base, with base value normalized at 1.0.

potassium ratio may not remain constant between trophic levels.[19,20] Cobalt, ruthenium, and zinc are slightly more concentrated in invertebrates than in water but are markedly less concentrated in invertebrates than in algae and higher plants. Comparable data for cobalt and ruthenium are nonexistent for aquatic vertebrates, and zinc does not appear to be further accumulated by the vertebrate links in food chains.

Biological Turnover

The "equilibrium" concentration of radionuclides along food chains is a function of the organisms' stable-element chemistry, but the rates of intake and turnover of isotope affect the time required for equilibrium to occur.[21] Rapid biological turnovers result in rapid equilibration; slow turnover of elements causes extension of the equilibration time. The radionuclide concentration, C_t, in an organism as a function of time is described by

$$C_t = \frac{IA_0}{\lambda_2 - \lambda_1} \left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) + C_0 \, e^{-\lambda_2 t} \qquad (2)$$

where C_0 = initial concentration of isotope in organism
I = intake rate of food (grams of food per gram of consumer per day)
A_0 = initial concentration of isotope in food
λ_1 = loss coefficient of isotope from food
λ_2 = loss coefficient for biological turnover of radionuclide by consumer organisms

Under the constraint that no previous body burden of isotope existed in the organism, the time required for equilibrium, $t_{\max}$, to be attained is

$$t_{\max} = \frac{1}{\lambda_2 - \lambda_1} \ln \frac{\lambda_2}{\lambda_1} \qquad \text{for } C_0 \equiv 0 \qquad (3)$$

The solution of Eq. 2 and the algebraic solution of its derivative Eq. 3 are dependent on knowledge of the biological loss coefficients, λ, which are defined as $\lambda = 0.693/T_b$, where T_b is the biological half-life of the radionuclide in the organism. A biological half-life is that time required for an organism to lose 50% of its body burden of a radionuclide when removed to a noncontaminated food source.

Metabolism

The biological turnover or excretion of elements is a basic metabolic process associated with the mineral nutrition of organisms. The rates at which elements and radionuclides are excreted are dependent on such intrinsic biological factors as body size, age, sex, physical activity, physical condition, and deposition in biological sinks. Extrinsic environmental factors affecting radionuclide turnover include chemical composition of the medium and temperature. Several of these factors have been identified for various radionuclides, but sufficient data are not available for all organisms and radionuclides to provide a complete picture. Many radionuclides can be grouped according to those characterized by long, intermediate, or short biological half-lives in various animal groups (Table 2). Some radionuclides were placed in more than one category in Table 2 either because their biological behavior is too variable to predict accurately or because factors influencing turnover could not be considered.

Considerable data exist for biological half-lives of some elements in insects for the size range of from 100 to 200 mg live weight that are based primarily on the cricket *Acheta domesticus* and the grasshopper *Melanoplus femur-rubrum*. Ordination of these values yields the following ranking, from long-lived to increasingly shorter lived nuclides:

$$\mathrm{I} > \mathrm{Zn} > \mathrm{Fe} > \mathrm{Na} \geqslant \mathrm{P} > \mathrm{K} \geqslant \mathrm{Cs} \geqslant \mathrm{Co} \geqslant \mathrm{Cr} > \mathrm{Ru} > \mathrm{Ca} > \mathrm{Sr}$$

In arthropods (millipedes and isopods) and other invertebrates (snails and clams) with highly calcified exoskeletons, both strontium and calcium have much longer biological half-lives (75 to 125 days) that are comparable to the overall values reported for zinc and manganese (Table 2) in all invertebrates. Iodine has rapid biological turnover by invertebrates, except in those forms with highly pigmented (melanin) cuticula; in such forms, significant iodine loss occurs only during molting. Other elements with characteristically slow biological turnover in invertebrate organisms are Co, Mn, Fe, and Zn. The alkali metals Na, K, Rb, and Cs generally have quite rapid biological half-lives.

Biological half-lives for radionuclides in aquatic invertebrates also illustrate the uniqueness between calcium sink and nonsink organisms. Manganese and strontium values were obtained from clams, where these two elements are accumulated in the shell but also have slow metabolic turnover. Biological behavior of the remaining isotopes is quite similar to that in terrestrial invertebrate organisms. Cobalt and zinc are involved in cofactors for enzyme systems and have relatively slow metabolic turnover. Phosphorus, calcium, and strontium have rapid turnover in species

Table 2 Biological Half-Lives of Elements in Major Groups of Organisms*

Animal group	Elements with indicated range of half-lives				
	0.1 to 1.0 day	1.0 to 10 days	10 to 100 days	100 to 1000 days	>1000 days
Aquatic					
Invertebrates†	Ca, Sr	P	Co, Zn, Cs (Sr and Mn)‡	Zn‡	Mn‡
Fish		Na, I	Na, K, Cs, I	Ca, Mn, Co, Zn, Sr, Cs	S, Co?, Sr
Terrestrial					
Invertebrates§	Rb, Sr, Y, Cu?	Na, P, K, Ca, Cr, Co, As, Sr, Y, Ru, Cs, I, W, Ir	Na, P, Fe, Co, Zn, (Ca and Sr),‡ I	I	
Vertebrates¶	B, Ge, Tc, Os	H, Li, C, O, Na, P, K, Sc, Mn, Co, Ga, Se, Br, Rb, Mo, Tc, Ru, Rh, Ag, Te, I, Cs, Re, Os, Hg, Tl, Bi	H, B, C, N, O, Na, Mg, Si, P, S, K, Sc, V, Mn, Fe, Co, Cu, Zn, Se, Rb, Ru, Rh, Pd, Ag, In, Sn, Sb, Te, I, Cs, Ba, Eu, W, Ir, Pt, At, Fr, U	F, Mg, Al, P, Ca, Ti, Cr, Mn, Fe, Ni, Zn, As, Sr, Zr, Nb, Cd, I, Cs, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Au, Pb, U	Ca, Sr, Y, Pb, Ra, Ac, Th, Pa, Np, Pu, Am, Cm, Bk, Cf

*Summary of literature values documented in Ref. 9.

†Primarily annelids and mollusks.

‡Invertebrates with calcified exoskeletons.

§Primarily adult insects.

¶Primarily homoiothermic vertebrates.

without well-developed exoskeltons. Fish possess bone sinks for calcium and strontium, as do their terrestrial vertebrate counterparts. The active metabolic pool of elements in soft tissues is divided into those with slow turnover (cobalt, zinc, and cesium) and those with rapid biological half-times (sodium and potassium).

Comparative data on biological half-lives of many elements are not available for a large number of mammalian species, but considerable information is available for various isotopes in species ranging in size from 8 g to about 900 kg. Many of the data in Table 1 are for man, and wider ranges of biological half-lives for many elements can be expected as additional excretion studies are performed with species having wider ranges of body size. Most of the elements with short biological half-lives concentrate in soft tissues, whereas the remainder with extended biological half-lives have long residence times in slowly metabolizing or inert tissues such as bone, teeth, or hair. Relatively short biological half-lives for cesium have been described for domesticated rabbits and species in the families Bovidae, Cervidae, and Suidae in the Artiodactyla. Similar consistently low values for iodine retention occur in these same groups. It appears that turnover of these elements (and perhaps others) may differ among mammal families. Practically nothing is known about radionuclide metabolism in about 10 of the 13 metazoan phyla, and much more experimental information is needed.

Body Size

A known variable affecting metabolism is body size, with metabolism a function of the 0.75 power of body weight.[22] Sufficient data were available for ^{134}Cs and ^{137}Cs biological half-lives in various organisms to obtain a coherent synthesis of the effect of body size on the turnover of this element. When these data on biological half-lives are plotted as a function of fresh weight of animals (Fig. 1), various groups of organisms form into rather discrete patterns. These groups represent organisms with distinct biological relationships. Group A consists of invertebrates other than insects and includes lower arthropods (millipedes, centipedes, isopods, and spiders) and mollusks (snails). Aquatic poikilothermic (cold-blooded) vertebrates in Group B include fish (perch, trout, bluegill, and carp) and one amphibian (newt). Group C is composed entirely of insects, ranging from sap-sucking aphids to saprophagous and herbivorous beetles, crickets, and grasshoppers. Warm-blooded (homoiothermic) vertebrates in Group D include rodents, lagomorphs (rabbits), artiodactyls (hoofed, even-toed mammals), primates (monkey and man), and chickens.

The biological half-lives plotted in Fig. 1 are those associated with the long component in excretion curves. This component is the most important quantitatively since the major residence time of assimilated radiocesium is determined by the slower rate component.[23] The shorter components in excretion curves represent unassimilated materials and the proportions of assimilated radionuclide which are turned over rapidly. Mathematical solutions of retention curves based on power functions provide better estimates of biological turnover for bone seekers than do calculations based on the assumption that retention decreases as a first-order exponential. The data were obtained from a number of literature and unpublished sources.[9] Some half-lives were measured in field experiments, but most were determined under controlled laboratory conditions. Biological half-lives (Y) for poikilotherms were adjusted to 20°C by using a Q_{10} of 2 (i.e., a doubling of the excretion rate and a halving of the turnover time for each 10°C increase in temperature). Such temperature adjustments, within the range of 10 to 25°C, were necessary for some data for insects and cold-blooded vertebrates.

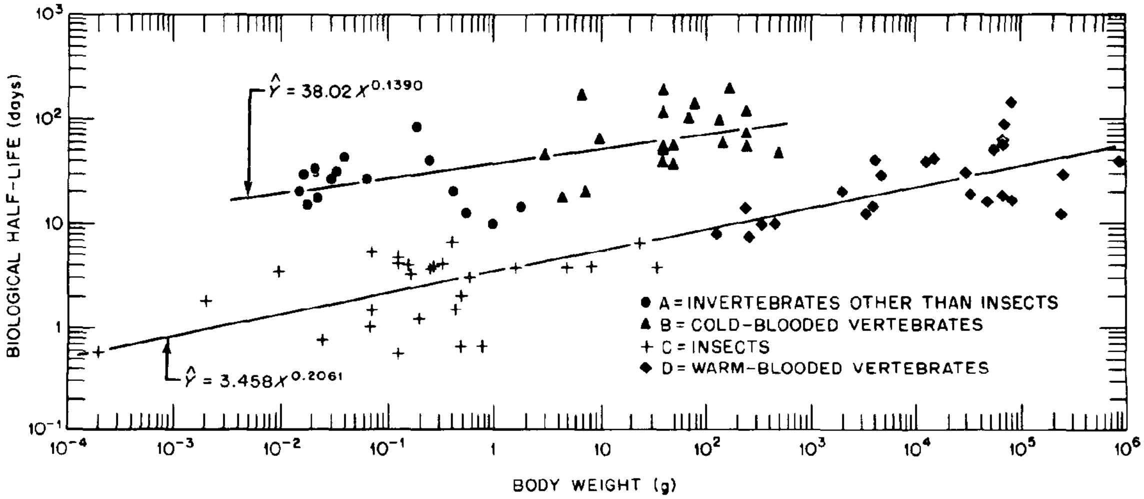


Fig. 1 Relation between animal body size and turnover of radiocesium. The graph of log cesium biological half-life against the log of live body weight follows a linear power function of the form $Y = aX^b$. Similar regression equations have been reported in the literature which relate metabolic rates of animals to body size. The data reported (see Ref. 9) are for poikilothermic (cold-blooded) invertebrates and vertebrates and homoiothermic (warm-blooded) vertebrates: Group A, invertebrates other than insects (primarily arthropods); Group B, aquatic vertebrates (predominantly fish); Group C insects; Group D, mammals and birds.

An encouraging aspect of the data in Fig. 1 is that the biological half-lives for cesium obtained in a variety of experiments are seemingly so consistent. In fitting a power-function model, $Y = aX^b$, to these data, the lower arthropods with calcified exoskeletons (Group A) are most closely associated with the cold-blooded vertebrates (Group B). Cesium turnover by insects (Group C) and warm-blooded vertebrates (Group D) are more closely related.[24] The regression equations calculated for these two combinations of organisms, where Y is the biological half-life of cesium in days and X is live body weight in grams, are, for Groups A + B,

$$\hat{Y}_{\mathrm{Cs}} = 38.02\, X^{0.1390} \qquad \text{SE* of } b = 0.03027$$

and, for Groups C + D,

$$\hat{Y}_{\mathrm{Cs}} = 3.458\, X^{0.2061} \qquad \text{SE of } b = 0.01499$$

Such size dependency for radionuclide turnover also can be interpreted from comparative data reported for a limited number of species and isotopes; for example, ^{110m}Ag, ^{131}I, ^{42}K, ^{22}Na, ^{86}Rb, ^{137}Cs, ^{65}Zn, ^{54}Mn, and ^{59}Fe in mammals (Refs. 25–31); ^{134}Cs and ^{137}Cs in arthropods (Refs. 24, 32, 33); and ^{137}Cs in aquatic invertebrates (Refs. 34, 35).

Strontium-90 and ^{131}I are two additional radionuclides of appreciable radiobiological interest because of their potential bioenvironmental hazard in waste releases. These radionuclides have been the subject of much research because ^{131}I is accumulated in the thyroid gland of vertebrates and ^{90}Sr is deposited in calcareous skeletal tissues. Research on these two isotopes typifies specific investigations involving biological sinks. The sinks are of contrasting types since ^{131}I possesses a short radioactive half-life and often is in an actively metabolized pool (thyroid), whereas ^{90}Sr is a long-lived radionuclide in a slowly exchanged metabolic pool (bone). Limited data are available on the whole-body turnover of these two elements. The whole-body retention data for ^{131}I and ^{90}Sr reflect the dominance of their respective sinks.

Biological half-lives of strontium were found for 11 species, including an arthropod, two mollusks, one amphibian, one fish, and six mammals (rats, monkeys, dog, and man). The resulting body-size power function equation is

$$\hat{Y}_{\mathrm{Sr}} = 107.4X^{0.2612} \qquad \text{SE of } b = 0.04720$$

A single regression appears satisfactory to describe the strontium values in these species (i.e., vertebrates, mollusks, and an isopod) and probably for other organisms with similar elemental sinks. Insects, which do not have highly calcified exoskeletons, generally have very rapid strontium half-lives of less than 1 day.[36]

Similar data for iodine (again using the long component T_b of whole-body retention curves) for 25 species, including insects, fish, and mammals, can be expressed by

$$\hat{Y}_{\mathrm{I}} = 6.819X^{0.1341} \qquad \text{SE of } b = 0.02408$$

The power-function equation describing iodine turnover fits the data for both vertebrates and invertebrates. Here the relationship holds because the biological half-lives for all species are dominated by metabolic pool size. Although in vertebrates the melanin pigmentation of skin and hair is an iodine sink, this is far obscured by the metabolically active thyroid pool. Similarly, the data for insects encompassed only lightly pigmented forms. In some insect species with considerable iodine incorporation in the extrametabolic sink of exoskeleton pigmentation, turnover of iodine occurs only at molting.

These results imply that body size, or some particular metabolic parameter correlated with body size, is an important factor in the biological turnover of cesium, strontium, and iodine in animals.

Effective Half-Life

For short-lived radionuclides where physical decay is significant, biological (λ_b) and radioactive (λ_r) loss coefficients are additive [e.g., $e^{-(\lambda_b+\lambda_r)}$], and the effective loss coefficient λ_e is equal to $\lambda_e = 0.693/T_e$, where

$$T_e = \frac{T_b T_r}{T_b + T_r} \tag{4}$$

The value of using an effective half-life in analysis of radionuclides in the environment cannot be overemphasized. For example, approximately 245 days would be required for physical decay to reduce the body burden of ^{65}Zn by 0.50 in an organism, whereas an effective half-life for zinc in a mammal of about 42 days (T_b = 100 days, Table 2) would yield a fractional remainder of less than 0.01 after that same period of time. For chronic releases of radionuclides, where the organism is in isotopic equilibrium with the environment, the critical variables are the radioactive half-life, quantity of radionuclide released, and the food-chain pathways. Under conditions of acute inputs of radionuclides, not only is the effective half-life important but also the longevity of the animal. Organisms with long life-spans may "outlive" short-lived radionuclides such as ^{125}I and ^{131}I, whereas organisms with brief generation times may never live long enough to accumulate dangerous body burdens of long-lived radionuclides such as ^{90}Sr. Radionuclides with relatively short effective half-lives can be hazardous to an individual if they are concentrated by specific tissues (e.g., ^{125}I or ^{131}I in thyroid). Other radioisotopes of elements that concentrate in gonads may increase mutations in populations (e.g., S, Zn, Te, and At in mammals).

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*SE = standard error.

Radionuclide Intake

Isotopic intake, I, and its equivalent food input are other variables necessary for the evaluation of Eq. 2. Intake was previously defined as grams of food per gram of consumer per day, but in the following example, we more simply define intake as r units of food mass or radioactivity per unit time. Intake (units of radioactivity per unit time) can be calculated from the uptake curve of uncontaminated animals feeding on a radioactive food source, by

$$ra = \frac{\lambda_b Q_t}{1 - e^{-\lambda_b}} \tag{5}$$

where Q_t is the body burden (units of radioactivity) in the organism after time t, and a is the proportion of ingested radionuclide assimilated from the intestinal tract into body tissues. Under conditions of chronic environmental contamination, where the organism is in isotopic equilibrium with its food base, intake (r) can be calculated from the mass-balance equation

$$r = \frac{\lambda_b Q_e}{a} \tag{6}$$

where Q_e is the equilibrium radionuclide body burden. Assimilation, a, cannot be considered equivalent for all radionuclides; digestive assimilation is highly variable, depending on the element, its chemical form, retention time of food in the gut, nature of the food eaten, age of the animal, etc.[24]

Terrestrial Organisms

Among terrestrial invertebrates, assimilation is variable according to the nature of the food base. For detritus, where most of the soluble constituents have been leached and those remaining are largely incorporated into poorly digestible tissue structures, assimilation is lowest; ^{134}Cs and ^{137}Cs are 53 to 65%, ^{90}Sr is 77%, and ^{47}Ca is 69%. Assimilation from dried meal is similarly low: ^{131}I is approximately 21% and ^{51}Cr is approximately 5%. Green foliage or similar herbaceous materials present a food base with an elemental content more readily available in the form of cellular constituents: ^{134}Cs and ^{137}Cs are 73 to 94% (~100% in sap-sucking aphids), ^{32}P is 54 to 66%, ^{86}Rb is 100%, and ^{187}W is approximately 100% (in sap-sucking bugs). Predators feeding on flesh show even higher assimilation efficiencies: ^{134}Cs and ^{137}Cs are 79 to 94%, and ^{47}Ca is 98%. Assimilation from water is characteristically high: ^{22}Na is 80%, ^{42}K is 97%, ^{134}Cs is 73%, and ^{187}W is 83%. Ruthenium-106 (30%) and ^{60}Co (25%) are elements that are poorly assimilated, as are ^{131}I and ^{51}Cr.

Assimilation of elements into mammalian tissues can occur via three routes: respiratory tract, skin, and gastrointestinal (GI) tract. Uptake by the latter route normally is the most important in natural environments. Inhaled material may be absorbed directly by lung tissues or moved by ciliated epithelium to the esophagus and ingested. Retention half-times for lung-absorbed materials of only a few days were found for ^{131}I, Ag^{131}I, ^{90}SrSO$_4$, and ^{210}PoOH, but materials such as ^{59}FeO$_2$, ^{239}PuO$_2$, RaSO$_4$, UO$_2$, and ^{106}RuO$_2$ had retention half-times of 100 to 1500 days.[37] Skin is apparently of minor importance in admitting most elements, although tritium and deuterium from atmospheric water enter freely.[38]

The lanthanide and actinide elements are poorly absorbed (<1%) through the GI tract walls, and so are the elements Be, Sc, Ti, Cr, Ga, Ge, Y, Zr, Nb, Cd, In, and La.[39] The lighter elements from atomic number 1 through 19 (except for Be, Mg, and Al) are absorbed well (70 to 100%), as are the elements Se, Br, Kr, Rb, Mo, I, Xe, Cs, Hg, At, and Fr. The remaining elements have intermediate absorbabilities. Uptake of some elements in herbivores is apparently affected by the physical condition or form of vegetation ingested by the animals.[16] Considerable diversity of radionuclide concentrations in mammalian herbivores and carnivores also should be expected because of varied feeding habits, such as seasonal changes in diet and selective feeding on tissues.

Aquatic Organisms

The intake of radionuclides by aquatic organisms occurs from either their food or direct uptake from water; with some elements, intake may occur by both modes. Uptake directly from water is known for sodium (Ref. 40) and strontium (Ref. 41). The gills of fish are a major site of ion exchange, although some absorption occurs through the body surface; in turtles the oral and cloacal mucosae serve as an exchange site.[40] With strontium the problem appears to be further complicated by food-chain movement. Dietary levels of strontium may significantly affect the strontium content of fish tissues.[42] Thus fish eating a strontium-rich diet would be expected to maintain a higher body burden of strontium.

Physical absorption is apparently of greater importance than biological absorption for the entry of radionuclides into algae.[43] Absorption appears to be a major mode of uptake for zooplankton as well. Thereafter, food-chain movement determines the environmental pathway for such radionuclides as ^{32}P, ^{137}Cs, ^{46}Sc, ^{76}As, ^{64}Cu, ^{51}Cr, ^{131}I, ^{65}Zn, and ^{144}Ce. Again there may be significant differences in assimilation because of the type of contaminated food consumed. Carp assimilate 80% of the ^{134}Cs on algae but only 7% from organic detritus associated with lake-bottom sediments.[44] Although ^{51}Cr appears to be assimilated at higher trophic levels in the Columbia River,[45] food-chain transfer was not observed in a marine amphipod.[46] The inability of fish to assimilate ^{144}Ce in ingested food was attributed to the incorporation of the ^{144}Ce in the undigestible exoskeleton of prey.[47] Thus the presence of metabolic sinks can affect the transfer of radionuclides in food chains. Marine amphipods assimilate ^{65}Zn (55.7%), ^{46}Sc (9.4%), and ^{144}Ce (6.2%) from contaminated brine shrimp.[46] White crappie may assimilate 100% of the ingested ^{42}K fed in goldfish.[19] Fish size also may be a factor, since bluegills weighing 80 to 120 g assimilate 91.6% of ^{137}Cs from chironomid larvae, whereas fish weighing 9 to 10 g and 0.5 to 1.2 g assimilate 70.6 and 34%, respectively, of ingested ^{137}Cs. Presently, data on radionuclide intake by aquatic organisms are too limited to draw more than a few generalizations, but apparently there are important differences between marine and freshwater environments. Also, the specific food chain involved appears to be a highly important factor in determining the ultimate pathway to man.

Discussion

Everyone agrees that unsafe levels of radioactive materials cannot acceptably be released into the living environment, but unanimity does not always exist about what constitutes "unsafe levels" in a particular environment. Our review indicates that considerable ignorance still obtains regarding uptake, assimilation, tissue distribution, turnover rates, and equilibrium levels for many taxonomic groups. Furthermore, additional effort should be expended on characterizing the effects of environmental factors on radionuclide cycling in selected ecological systems, particularly in highly populated riparian and coastal areas where power-reactor complexes most likely will be placed.

Multiplication of human populations and acceleration of man's activities are causing increasing complexities and stresses in many environments. Imposition of additional pressures, such as those resulting from reactor effluents, on ecological systems will cause further interactions between components of these ecosystems. Consequently proliferation of reactor construction and consequent increases in radioactive waste-disposal operations in this atomic age will require even more sophisticated evaluations of future nuclear installations and procedures. These evaluations, although primarily concerned with man's safety, must also consider the biota around man because it is upon this living environment that human beings must depend.

Evaluation of the hazard to humans will require a coherent theory, as well as predictive mathematical models, of radionuclide cycling in the environment.[48] Limited data are available for various aspects of the biological uptake and translocation of radionuclides in segments of environmental cycles, especially those cycles (food chains) leading to man.[49] It is one matter to know that food chains are important but quite a different matter to quantify these complex chains for natural and agricultural ecosystems.[50] It is not that we lack sophisticated mathematical techniques (e.g., the compartment models of systems analysis) to develop predictive models of ecosystem processes, but rather that we have neither sufficiently detailed nor widely representative radioecological data with which to work.

Analogous to the food chain (source–pathway–receptor), the parameters required for modeling the biological transport of radionuclides in the environment include (1) pathway identification, (2) assimilation at each link in the pathway, and (3) the turnover rates of radionuclides by the receptor organisms. The second and third factors will determine the net uptake rate and the eventual radionuclide concentration in organisms. Acute releases of radionuclides into the environment are followed by transient peaks of radioactivity along the food-chain pathways.[21] Knowledge of these pathways, assimilation, and turnover rates of radionuclides are essential for prediction of time-dependent concentrations in the biota. Chronic releases will result in steady-state concentrations in the biota, and, in these instances, concentration factors can be used to approximate the eventual equilibrium levels of radioactivity.

Distinction must be made between elemental concentration in organisms [e.g., parts per million (ppm)] and concentration factors for elements in the environment (e.g., ratio of ppm in organism to ppm in environment). Some organisms have relatively constant whole-body elemental compositions over a broad range of environmental conditions. The concentration factors for these elements are, therefore, biologically determinant; that is, the concentration factors will be inversely proportional to the concentration of the respective elements in the environment. Calcium and potassium appear to be two such elements that are relatively conservative in their concentration in fish.[51,52] Conversely, the concentration of strontium in fish flesh appears to be biologically indeterminant since uptake is directly proportional to the concentration of strontium in the environment;[53] thus the concentration factor remains constant. Further development of these concepts and identification of those elements which have either determinant or indeterminant concentrations can result in a considerable simplification of the data requirements for the modeling of steady-state systems.

Applications of approaches such as those discussed here will help to (1) design preliminary tests of radionuclide transfer in geographic regions of interest and (2) establish realistic predictive guidelines for reactor siting, radioactive waste disposal, Plowshare projects, and ameliorative actions after accidents. So far, nuclear operations have been among the best regulated and safest of industries, and we cannot be less careful in the future.

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MOVEMENT OF FALLOUT RADIONUCLIDES THROUGH THE BIOSPHERE AND MAN[1]

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INTRODUCTION

Possible sources of man-made environmental radiocontamination include nuclear explosions, manufacture and processing of nuclear fuel, reactor operation and accidents, use of nuclear power sources in space vehicles, and disposal of radioactive wastes (1, 2). To date, by far the major source has been radioactive debris (fallout) from the testing of nuclear weapons, and considerable information on this subject has become available, many aspects of which, however, are pertinent for other sources.

In regard to radioactive fallout the main objective has been to understand the relationships between amounts and patterns of release and the harm that may be caused to the human population. There has been need to monitor the environment, to make predictions as to what will happen from known or anticipated injections of contamination into the environment, and to know how to reduce the exposure of man. An overall assessment requires consideration of the physicochemical properties of the radionuclides, physical transport through the atmosphere, entry into man's food, entry and retention in man, and finally the biological effects on man. The present review is limited primarily to the movement of fallout radionuclides from the time they reach the surface of the earth until they are retained in man.

The entire scope of the problem has been dealt with in recent reviews (3–12). In particular the reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (3, 4) present comprehensive coverage with extensive bibliographies which permit the documentation in the present review to be selective. In addition, there are several useful serial publications, mostly of governmental origin and dealing with assays of biospheric samples (13–16).

Fission product debris or fallout is classified as stratospheric, tropospheric, or local. Most of the radioactive debris produced during 1961–62 resulted from high-yield weapons and was injected into the stratosphere; this, together with previous stratospheric fallout, constitutes the main source of world-wide contamination (4). Tropospheric fallout takes place within a month after production in an irregular band at about the same latitude as the detonation; it is of lesser importance, except in special instances, since it is produced by weapons of less than 1 megaton yield, which represent less than 10 per cent of those tested. Local fallout is essentially restricted to

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[1] The survey of literature pertaining to this review was concluded in January 1965.

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the site of the explosion, and has not contributed significantly to the general contamination of the biopshere.

To give an idea of the amounts of radioactivity released from weapons tests conducted in the atmosphere by all nations, the approximate yields have been as follows: (*a*) 1945–58—air burst, 38 megatons fission yield out of a total of 69 megatons—surface burst, 54 fission yield out of 105; (*b*) 1961–62—air burst, 101 fission yield out of 337 (4). This has resulted in an estimated inventory of Sr^{90}, as of January 1964 and corrected for decay, as follows: total atmosphere—4.3 megacuries; world-wide deposition—9.0 megacuries; Northern Hemisphere (0–80° N)—31 millicuries/km^2; Southern Hemisphere (0–50° S)—7.7 millicuries/km^2 (4).

The 200 or so fallout radionuclides can include those present as original fissionable material and those produced by fission or activation. Only a few of them are considered to represent a possible hazard to man through their appearance in fallout from nuclear tests; their potential importance is determined by: (*a*) production yield; (*b*) half life; (*c*) extent to which they enter parts of plants consumed by animals and man; (*d*) extent to which they enter human food of animal origin; (*e*) extent to which they enter man; (*f*) degree and pattern of retention in man; and (*g*) radiosensitivity of tissues of retention. On this basis, emphasis has been given to Sr^{90}, Cs^{137}, I^{131}, and C^{14} with less attention to Sr^{89} and others.

PATHWAYS IN GENERAL

Although the movement of the various radionuclides through the food chain is dependent upon specific metabolic properties, some generalizations can be made (17–21). The transfer rate of radionuclides from the stratosphere to the ground level depends upon the altitude reached by them and the latitude of explosion; mean residence times have been estimated as follows: material above 100 km—>5 years; material in lower stratosphere—<1 year; overall average—2 years (4). After entering the troposphere from above, the fission products are transported to the level of rain-bearing clouds by turbulent mixing, and below this level the particles are rapidly deposited by precipitation. Strontium-90 deposition has been shown to be roughly proportional to the amount of precipitation: this relationship is better when comparisons are made in the same general climatic region (4). Dry removal can occur, and is affected by such factors as microturbulence and vegetation cover. However, dry deposition is important only in areas of low rainfall.

There are two important ways in which plants may become contaminated by fission products from the atmosphere: (*a*) indirect contamination, which occurs when radioactive material enters the soil and passes into the plant through the roots as do soil nutrients; (*b*) direct contamination, in which passage through the soil is by-passed. Direct contamination reflects events of the recent past; it varies with the rate at which fallout settles and is designated as "rate-dependent." Indirect contamination is governed by the total amount available in the soil and is designated as "cumulative-dependent." Indirect contamination further differs in that: (*a*) material deposited before the plant develops can enter the plant; (*b*) short-lived radionuclides that enter the soil do not contribute significantly to radioactivity of diets because of radioactive decay during the time required for them to reach the roots; (*c*) the radioactive substances that enter the soil can be diluted with soil substances, rendered unavailable to the plant by fixation to soil minerals, or discriminated against in plant uptake; e.g. no plants have been reported to absorb from the soil as much as 10 per cent of the applied dose of fission products (17).

Attempts have been made to predict future levels of radionuclides in various parts of the biosphere and to evaluate the "cumulative" and "rate" contributions by expressions of the form:

$$C = p_d F_d + p_r F_r \qquad 1.$$

where

C = concentration of radionuclide in the sample of interest
F_d = cumulative deposition (usually mCi/km^2)
F_r = current rate of deposition (usually mCi/km^2/year)
p_d *and* p_r = proportionality factors.

Estimated values of p_d and p_r for Sr^{90} and Cs^{137} are presented in Table I. Despite uncertainties and limitations this type of calculation has been useful (3, 4).

Radionuclides in or on plants may reach man directly by his consumption of foods of plant origin or indirectly by his consumption of animal products. The grazing animal effectively collects contamination from plant material and concentrates it in animal products. Various factors, such as the metabolic behavior of the specific nuclide and animal feeding and management practices, then influence the relationship between the amount of radionuclides eaten by the animal and the amount deposited in tissues and in secretions, such as milk, which are used for food. General principles that govern the entry and deposition of radioactivity in domestic animals have been reviewed (18).

The secretions of Sr^{90}, Sr^{89}, Cs^{137}, and I^{131} into milk have received considerable attention. Fallout radionuclides from a single event are deposited on pasture over a relatively short period of time. Estimates are needed of the following: (*a*) the concentrations at various times in the milk of cows allowed to remain on the pasture; (*b*) the concentrations when the animals are moved to uncontaminated feed; (*c*) the integrated intakes by man consuming milk from these animals; and (*d*) the time periods required for the levels in milk to be reduced by certain factors.

It is first necessary to have equations that represent the concentrations in milk as a function of the amount ingested. Such equations have been developed from controlled single or chronic feeding experiments, and the principles of interconversion of data have been discussed (18); also needed are

TABLE I

ESTIMATED PROPORTIONALITY FACTORS FOR CALCULATION OF FUTURE LEVELS DERIVED FROM SURVEY MEASUREMENTS (3, 5)

I. *Sr^{90} equation:* $C = p_d F_d + p_r F_r$

C = yearly average Sr^{90}/Ca (pCi/g) in foodstuff listed
F_d = total accumulated deposit of Sr^{90} in soil in mCi/km²
F_r = yearly fallout rate of Sr^{90} in mCi/km² in given year
p_d, p_r = corresponding proportionality factors

	p_d	p_r
Milk	0.3	0.8
Vegetables	1	1
Starchy roots	1	0
Unmilled cereals	0	20
Diet (milled cereal)	0.4	1.1
Diet (unmilled cereal)	0.4	1.8

II. *Cs^{137} equation:* $C' = p_r' F_r' + p_{2c}' F_{2c}'$

C' = average concentration in given year
F_r' = fallout rate of Cs^{137} in given year in mCi/km²
F_{2c}' = total Cs^{137} accumulated over previous two years in mCi/km²
p_r', p_{2c}' = corresponding proportionality factors

	p_r'	p_{2c}'
Milk (C' in pCi of Cs^{137}/liter)	3.6	0.65
Man (C' in pCi of Cs^{137}/g of K)	1.9	3.0

equations for the radioactivity in milk as a function of time after cessation of intake. It is then necessary to take into account the rate of loss of radioactivity from the pasture which has been shown to be exponential (22, p. 61); a half-time of removal of 14 days (factor $= e^{-0.05t}$) is used on the basis of reported values. Finally, the factor for radioactive decay must be included for Sr^{89} and I^{131}.

From data in the literature and additional unpublished experiments with five to ten cows for each situtation where needed, the following equations essentially summarize available metabolic data and permit approximations (F. W. Lengemann, personal communication).

(*a*) C = picocuries of radionuclide per liter of milk if cow ingests 100 pCi on the first day and is allowed to remain on contaminated pasture for t days.

$$Sr^{90} \quad C = 0.1e^{0.0085t}(1 - e^{-0.26t})(e^{-0.05t}) \tag{2.}$$

$$Sr^{89} \quad C = 0.1e^{0.0085t}(1 - e^{-0.26t})(e^{-0.05t})(e^{-0.018t}) \tag{3.}$$

$$Cs^{137} \quad C = 1.6e^{0.0014t}(1 - e^{-0.26t})(e^{-0.05t}) \tag{4.}$$

$$I^{131} \quad C = 0.9e^{0.02t}(1 - e^{-0.29t})(e^{-0.05t})(e^{-0.086t}) \tag{5.}$$

(*b*) C' = picocuries of radionuclide per liter of milk if cow is moved to an uncontaminated pasture when the milk contains M picocuries per liter (t = days after being moved).

$$\mathrm{Sr}^{90} \quad C' = M(0.993e^{-0.37t} + 0.007e^{-0.01t}) \tag{6.}$$

$$\mathrm{Sr}^{89} \quad C' = M(0.993e^{-0.37t} + 0.007e^{-0.01t})(e^{-0.013t}) \tag{7.}$$

$$\mathrm{Cs}^{137} \quad C' = M(0.72e^{-0.37t} + 0.25e^{-0.17t} + 0.034e^{-0.02t}) \tag{8.}$$

$$\mathrm{I}^{131} \quad C' = M(0.9e^{-0.78t} + 0.1e^{-0.1t})(e^{-0.086t}) \tag{9.}$$

Table II presents some results deduced from these equations. Note that estimates of human intake are expressed in terms of concentrations in milk since these can be readily measured, whereas intakes of radionuclides by the cow cannot generally be estimated.

TABLE II

ESTIMATES OF CHANGE IN RADIONUCLIDE LEVELS IN MILK AND HUMAN CONSUMPTION WHEN COWS REMAIN OR ARE REMOVED FROM CONTAMINATED PASTURE[a]

	Sr^{90}	Sr^{89}	Cs^{137}	I^{131}
I. *Cows remain on contaminated pasture:*				
Days to reach peak level in milk	7	7	6	3
Lifetime intake by man who consumes 1 liter of milk per day (P = peak level in milk)	$33\times P$	$27\times P$	$32\times P$	$15\times P$
Intake by man who stops consumption immediately after peak level is reached	$6.9\times P$	$4.3\times P$	$5.1\times P$	$2.4\times P$
Days to reduce level by factor of 10	67	52	66	32
Days to reduce level by factor of 100	124	94	125	60
II. *Cows removed from contaminated pasture at time of peak level:*				
Lifetime intake by man who consumes 1 liter of milk per day (P = level at time of shift)	$7.7\times P$	$7.2\times P$	$10.2\times P$	$4.0\times P$
Days (after removal) to reduce level by a factor of 10	6	6	8	3.5
Days (after removal) to reduce level by a factor of 100	14	13	49	13

[a] F. W. Lengemann, personal communication.

Man can also receive contamination through his consumption of fisheries' products and by inhalation, but these are not considered important contributors to radiation exposure. However, the presence of fallout particles in adult human lung has recently been demonstrated by autoradiography (23).

STRONTIUM 90

STRONTIUM AND CALCIUM RELATIONSHIPS

In biological systems the behavior of stable strontium, and therefore of the fallout Sr^{90} that equilibrates with it, is similar to and is governed by the behavior of calcium. Because of homeostatic control there is a remarkable constancy of calcium in many tissues and fluids (e.g. blood and milk). Thus it can be generalized that within normal dietary ranges the fallout Sr^{90}-to-calcium ratio in the body tissues or secretions is directly related to the ratio that exists in the diet. This concept has been well reviewed (24–29). For these reasons the concentrations of Sr^{90} in biological materials are often reported as a Sr/Ca ratio (picocuries of Sr^{90} per gram of calcium).

Biological organisms generally utilize and retain strontium less effectively than calcium; the term "discrimination" is used to denote this behavior (30). Several modes of expression have been used (31, 32); the following terminology defines not only the overall discrimination, but also the contributions of the individual physiological processes that produce it.

The overall discrimination is designated as the "Strontium-Calcium Observed Ratio" (*OR*):

$$OR_{\text{sample/precursor}} = \frac{\text{Sr/Ca sample}}{\text{Sr/Ca precursor}} \qquad 10.$$

It is important in the estimation of *OR* values that the Sr/Ca ratios as measured truly represent the ratio as actually available to the organism and as actually derived from a single precursor. To denote the discrimination produced by a given physiological process, the term "Strontium-Calcium Discrimination Factor" is used and defined as:

$$OR = (DF_1)(DF_2)(DF_3) \cdots (DF_n) \qquad 11.$$

The *DF* values are given specific names to denote the physiological process involved (see later discussion of $OR_{\text{milk/diet}}$ for an example).

The Observed Ratios and Discrimination Factors deal with the amounts of strontium and calcium that move across physiological barriers under conditions of their passage through the biological system. Recently comparisons have been made of rates of transport by consideration of fractional rate constants, and these related to *OR* and *DF* values (33, 34, 35). If it is assumed that the rates of Sr and Ca movement across a barrier follow first-order kinetics and that the rate constants for each are related to each other in the same way at each site of movement, then it can be shown that:

$$\frac{\text{Sr}}{\text{Sr}_0} = \left(\frac{\text{Ca}}{\text{Ca}_0}\right)^K \qquad 12.$$

and

$$DF_{\text{absorptive}} = \frac{1 - (\text{Ca}/\text{Ca}_0)^K}{1 - \text{Ca}/\text{Ca}_0} \qquad 13.$$

where

Sr_0 and Ca_0 = amounts of strontium and calcium present at 0 time in the compartment from which transport occurs

Sr and Ca = amounts of strontium and calcium present at some later time in the compartment from which transport occurs

k_{Sr} and k_{Ca} = rate constants representing fractional rates of movement of strontium and calcium across the barrier

$K = k_{\text{Sr}}/k_{\text{Ca}}$

Equation 12 was shown to hold reasonably well for renal tubular reabsorption in man and dogs (33) and also for gastrointestinal absorption in rats (34). In all instances, the value of $k_{\text{Sr}}/k_{\text{Ca}}$ was about 0.7. Such data suggest, although it is not yet proved, that the same discriminating mechanisms operate in both the kidney and the gastrointestinal tract. These relationships show how the discrimination factors and the OR values can vary according to the degree of absorption. For example, it has been calculated that in the rat, if the calcium absorption is increased from 20 to 90 per cent, the value of $DF_{\text{absorptive}}$ is increased from 0.70 to 0.89 (35). This response may account in some measure for the finding that values of $OR_{\text{body/diet}}$ are generally increased under conditions of increased calcium absorption, for example, in the young individual or following treatment with substances such as vitamin D and lactose as mentioned later. Thus, any treatment that alters absorptive discrimination can do so in two ways: by changing the absorption of both alkaline earths proportionally, and by changing the comparative rate constants of strontium and calcium transport. Application of the above equations should allow one to distinguish between these effects.

It has been recognized for many years that the value of $OR_{\text{body/diet}}$ can be varied. In rats, pigs, and man the $OR_{\text{body/diet}}$ is higher in the very young than in the adult, primarily because of decreased absorptive discrimination in the young (21, 36–39). In numerous studies with rats it has been shown that the calcium absorption and the $OR_{\text{body/diet}}$ value are increased by milk, certain amino acids (particularly lysine and arginine), and certain carbohydrates, particularly lactose (24). However, supplementation of basal diets of rats with lysine did not increase net retentions of stable calcium, Ca^{45}, or Sr^{85} (40) and there was no difference in calcium absorption in rats on milk and nonmilk diets (26). In studies with man, lysine or lactose had little, if any, effect on calcium and strontium absorption (41, 42). These apparently conflicting results probably arise because of the numerous factors that affect alkaline earth absorption and the difficulty of controlling them in experiments (43). As an outgrowth of studies in which increased dietary calcium was shown to reduce body burdens of Sr^{90} (44), numerous workers, especially from Kornberg's laboratory, have shown that the $OR_{\text{body/diet}}$ in rats is complexly variable as an interrelated function of age, calcium level, and Ca/P ratio (24, 39, 45). Recently the importance of dietary phosphorus for both the absorptive and renal discrimination has been demonstrated in rats (46) and this factor has been studied in man (47).

Despite variations in OR values it appears that they fall within reasonably narrow ranges under usual dietary conditions and are consistent enough to be meaningful for prediction of radiation effects, which involve uncertainties of a much higher order. Strontium-calcium relationships have been found useful in: (*a*) developing systems of integrating samples, for instance, the determination of Sr/Ca ratios in pooled urine samples to permit calculations of dietary intakes; (*b*) estimation of body burdens and particularly maximum Sr^{90} concentrations in local areas of newly formed bone; and (*c*) prediction of effects of changing dietary Sr^{90}/Ca ratios (24). It is important, to permit full interpretations, that Sr^{90} data be reported on bases of both calcium content and unit sample weight whenever possible.

SOILS and PLANTS

Basic knowledge of the movement of Sr^{90} in soils and plants was fairly well crystallized prior to 1963; there has been detailed and excellent coverage in several reviews to which reference can be made for support of statements in this section not otherwise documented (3, 4, 5, 17, 19, 48).

Absorption from soil (indirect contamination).—The absorption of strontium and calcium from soil is affected by the clay content, humus content, pH, moisture level, concentration of electrolytes, and especially the calcium content. Conditions that lead to shallow root development tend to increase Sr^{90} absorption.

The amount of Sr^{90} entering plant crops per year is estimated to range from 0.2 to 3 per cent of that in the soil. It is judged that plants will likely contain about 1.1 pCi of Sr^{90} per gram of calcium if 1 mCi of Sr^{90} per square kilometer is present in soil. The uptake of Sr^{90} is generally greatest from soils of low calcium content; the addition of lime to such soils can reduce the Sr^{90} uptake by factors of up to three. However, when soils contain adequate calcium for the growth of crops, the addition of lime causes little or no reduction in Sr^{90} uptake. The addition of fertilizers and organic matter in large amounts has varying effects, but at agricultural levels only small effects.

The downward movement of Sr^{90} in undisturbed soil is slow and most of it is retained in the upper few centimeters even after several years. Downward movement is accelerated by low contents of clay and humus, high levels of electrolytes, and rapid movement of water. In shallow-rooted plants the Sr^{90}/Ca ratio was reduced by a factor of up to 3 by plowing to a depth of 28 to 30 cm, as compared to surface placement; in more deeply rooted crops the effect was smaller. There has been some evidence that Sr^{90} in soil may become less available for plant uptake with time because of fixation processes; if this effect is real, it is so small as to have little practical significance. The suitability of soils for the disposal of radioactive strontium wastes has been considered, with attention given to soils of arid and semi-arid regions containing high concentrations of calcium carbonate (49).

The average values of $OR_{\text{plant tops/solution}}$ and $OR_{\text{plant tops/soil}}$ are probably close to one; however, deviations have been reported which appear to have been caused by difficulties of estimating the relative availabilities of the strontium and calcium in the soil. The Sr/Ca ratios vary consistently between different tissues of the plant; compared to leaf tissue the Sr^{90}/Ca ratios are higher in roots and stems and lower in fruits, grains, and seeds. These discriminatory processes appear to be of little practical significance.

Controlled pot studies with barley, wheat, and soybeans have shown that genotype differences do exist in the accumulation of radioactive strontium from soil (50, 51). The magnitude of the differences, up to about fourfold, suggested that there might be an advantage under some conditions of growing varieties that would deposit less than normal amounts of Sr^{90} in their edible parts; unfortunately these authors did not report the corresponding calcium relationships. When 36 species of plants including cereal crops, forage crops, and vegetable crops were grown in contaminated soil, there was considerable variation in the Sr^{90} contents, but the Sr^{90} per gram of calcium was reasonably constant for most species (52). More recently, however, differences in Sr^{89}, Ca, and Sr^{89}/Ca ratios were reported for different varieties of barley and wheat (53).

Direct contamination of plants.—Direct contamination results primarily from finely divided soluble deposits such as are found in world-wide fallout, since particles larger than 40 μ are only slightly retained. The extent of contamination depends upon the nature of the rainfall and the surface area and characteristics of exposed plant tissue; an illustrative relationship between climatic conditions and Sr^{90} levels in wheat has been reported (54).

Foliar contamination refers to the retention of Sr^{90} on leaves. Experimental studies have shown that about 25 per cent of the Sr^{90} deposited in rain may initially lodge on that part of permanent pasture consumed by grazing animals. Absorption into leaves is slow and translocation within the plant negligible. Losses readily occur, especially in subsequent rain; these have been described as exponential with a rate constant of about 5 per cent per day. Although leaching in rain is the major cause of loss, it has been demonstrated that small losses can occur even if plants are kept under dry conditions (55).

Floral contamination, or retention by inflorescences, is of practical importance only for grain crops. It accounts for the high Sr^{90}/Ca ratio in grain and flour as compared to vegetables, and in bran as compared to flour. It has also been shown to be important for rice. In 1959, 20 to 90 per cent of the Sr^{90} in grain from different parts of the United States was judged to have resulted from direct contamination (48), and from 1957–60 this value for Canadian wheat was more than 40 per cent, as shown by ratios of Sr^{90} to stable strontium (56).

Plant-base absorption refers to the absorption of material that washes down from leaves or is retained from rain in the axils of leaves, the crowns of plants, or the root mat. Material may be absorbed from the plant-base reservoir over relatively long periods of time as compared to the more restricted periods of foliar or floral absorption which are limited to the period of actual contact between the exposed tissue and the contaminating medium. Also, Sr^{90} that enters by plant-base absorption is translocated within the plant. Plant-base absorption has been claimed as the dominant pathway in pastures on the basis of correlation analyses between Sr^{90} levels in milk and rates of deposition (48). Strontium 90 is thought to accumulate in cabbages mainly by the lodging of rain in cavities at leaf axils, and in potato tubers by the downward leaching by rain over the stem surfaces. Radioactive strontium deposited on potato foliage was shown to undergo foliar leaching and subsequent accumulation in underground tubers by root absorption (57). This, then, represents a means by which underground tissues can become contaminated from fallout.

AQUATIC FOOD CHAINS

Comparatively little attention has been given to aquatic food chains, since fisheries products furnish little Sr^{90} in most human diets; for example, in New York City it was estimated that the Sr^{90} contributed by fresh fish ranged from 0.001 to 0.14 per cent of the total Sr^{90} intake during the years 1960–63 (14, Vol. 147). The main interest has been in relation to discharges from nuclear facilities and to situations near the sites of weapons tests (1, 3, 4, 9, 58–61).

Strontium-90 concentrations in a Norwegian lake were shown to be about 10 per cent of those in precipitation; however, during periods of flooding the concentrations increased substantially because of a decreased exchange of Sr^{90} between the surface water and the soil before the arrival of the water to the lake (4). Average values for USSR rivers in 1961–62 ranged from 0.5–0.9 pCi/liter. It is assumed on the basis of much evidence that the fallout rate over the ocean is the same as that over land; however, some observations of higher levels of Sr^{90} in deep waters remain unexplained by this assumption (4).

The bones, scales, and shells of marine organisms concentrate Sr^{90} manyfold over the concentration existing in the environment; the flesh does not. The steady state concentration in flesh is usually less than one-tenth that in the surrounding water. Values of $OR_{\text{body/water}}$ for fish have been estimated as 0.2 to 0.4 (3). In a recent study with brown trout taken from various waters in the United Kingdom, it was shown that the $OR_{\text{muscle/water}}$ varied from 0.53 to 1.00 as the calcium concentration in the water varied from 0.3 to 100 mg/liter, whereas the $OR_{\text{bone/water}}$ was about 0.5 in all samples and thus independent of the calcium levels (62). Further work showed that the concentration of strontium in bone and muscle was inversely related to the calcium concentration of the water, and predictions were presented for the Sr^{90} in muscle tissue of brown trout under varying conditions of calcium and Sr^{90} concentration (63).

ANIMAL PRODUCTS

Secretion into milk.—The extent to which ingested radiostrontium is secreted into the milk of dairy animals is of great practical importance and, for this reason, considerable experimental work has been done in this area over the past few years. The findings have been reviewed (35, 64) and can be summarized as follows.

Following ingestion of a single dose the maximum concentration of Sr^{90} in the milk of the dairy cow is reached at about 48 hr and is approximately 0.02 per cent of the dose per liter of milk. The level then falls regularly and is only a few per cent of the peak concentration by 15 days. Thus, at 15 days after the start of chronic ingestion the level of Sr^{90} reaches a plateau.

The total amount of ingested Sr^{90} appearing in milk ranges from 0.3–4 per cent of the dose within species for the cow, goat, and man. This quantity is related to milk yield which accounts for the variability. A more constant and useful measure is obtained by expression in terms of per cent of daily intake per liter of milk; typical values on normal diets are about 0.1 for the cow, 1.4 for the goat, and 0.27 for man. The value for the goat is more than ten times higher than for the cow because the former puts a much larger proportion of its dietary calcium into the milk per liter than does the cow. This differential behavior is of little practical importance from the standpoint of environmental contamination because the $OR_{\mathrm{milk/diet}}$ values are essentially the same for the two species. Therefore, if the cow and goat consume the same feeding stuffs (i.e. feeds with the same Sr^{90}/Ca ratio) there will be about the same Sr^{90}/Ca ratio in the milk of the two species. The amount of ingested calcium and strontium appearing in the milk is inversely related to the dietary calcium level because the calcium concentration in milk is essentially constant, regardless of dietary intake. Equations 2, 3, 6, 7 and Table II summarize available data on secretion of Sr^{90} and Sr^{89} into the milk of the dairy cow.

From a practical standpoint the $OR_{\mathrm{milk/diet}}$ is of greatest importance. Values of $OR_{\mathrm{milk/diet}}$ for the cow, goat, and pig, as determined by various methods and by a number of investigators, range from 0.08–0.16 with most values near 0.1. This overall discrimination from the diet to the milk in the cow is brought about primarily by absorptive discrimination ($DF_{\mathrm{absorptive}} = 0.25$) with a lesser contribution by urinary and lactational discrimination ($DF_{\mathrm{urinary}} = 0.7$; $DF_{\mathrm{lactation/milk}} = 0.7$). The $OR_{\mathrm{milk/plasma}}$ values for the goat and cow are 0.4–0.6, with evidence that the discrimination occurs unidirectionally by means of preferential movement of calcium over strontium from blood to milk.

In regard to the state of alkaline earths in milk, it has been shown that 70–80 per cent of milk calcium was bound to casein and that about 20 per cent was ultrafiltrable (65). Strontium was bound to casein to a greater extent than was calcium. It was shown that Sr^{85} and Ca^{45}, when added to milk, did not completely exchange with those ions already present. This means that the mammary gland builds Ca^{45} and presumably Sr^{90} into that portion of the caseinate colloid found to be nonexchangeable *in vitro*. However, the amounts that are nonexchangeable are relatively small.

There has been considerable interest in the feasibility of procedures for reducing the concentrations in milk that result from chronic ingestion of Sr^{90}. In a long-term study with lactating cows raised from calves, it was shown that, within normal dietary limits (50–120 g/day), the amount of ingested radiostrontium (Sr*) secreted into milk was inversely proportional to the dietary calcium level. This confirms predictions from earlier short-term studies in which the $OR_{\text{milk/diet}}$ was the same in cows receiving 45 g Ca, 90 g Ca, 280 g Ca, or 45 g Ca plus 494 g Sr per day. From a practical standpoint, mineral supplementation with calcium appropriately carried out might be capable of reducing Sr^{90} levels in milk by a factor of about 2, but probably not more than 4 at the most because of abnormality of diets (64). The question is often raised whether stable strontium is advantageous for reducing the entry of radiostrontium into milk. Because strontium deposition is governed by the levels of calcium plus stable strontium, rather than by stable strontium itself, no reduction in the secretion of radiostrontium can be expected from any reasonable increase in stable strontium intake (24).

It is important to know the sequence of events following supplementation with calcium. An abrupt increase of uncontaminated calcium in the diet of the cow was found to cause an immediate decrease in the radiostrontium content of milk; however, the new Sr*/Ca ratio in milk may not be as low as that expected after long-term feeding because of the contribution of the body stores to the strontium and calcium of the milk. Thus, for example, a dairy cow secreting about 0.2 per cent of ingested Sr^{85} per liter was found to secrete about 0.13 per cent when the dietary calcium was increased by a factor of 2.5; the steady state level should have been 0.08 per cent per liter (64).

A number of chemical substances known to react or compete with calcium and strontium have been fed to lactating cows and goats to determine the effects on the secretion of strontium into milk. These include such substances as the sodium salt of EDTA, potassium acid phosphate, ion exchange resins, and magnesium sulfate. It was concluded that these substances do not offer any practical means of reducing levels of fallout radiostrontium appearing in milk. Varying effects have been seen by treatment with parathormone, cortisone, and calcium injections but, again, none of these appeared to offer practical possibilities (C. L. Comar, unpublished data). It has been reported that the feeding of 5–10 per cent of exfoliated vermiculite ores to sheep caused a decrease in radiostrontium absorption (66). However, further work is necessary to determine whether the procedure would permit adequate calcium absorption while at the same time decreasing the radiostrontium uptake.

The importance of farming practices is demonstrated by studies conducted over a three-year period that have shown that levels of Sr^{90} and I^{131} in milk can be moderated by optimal fertilization of the land (67). In controlled experiments, milk from cows grazing on abundant, well-fertilized pastures contained 50 per cent or less of these radionuclides than did milk from cows grazing on unfertilized pastures on the same farm. The dilution of fission product contamination in the larger volume of faster-growing fertilized forage was shown to account for the differences in the milk.

Deposition in meat and eggs.—Little research has been done on deposition in meat and eggs because they contribute relatively minor amounts of radiostrontium to the human diet. Values of $OR_{\text{edible tissue/diet}}$ for animals are essentially the same as the values of $OR_{\text{body/diet}}$ since there is virtually no discrimination in the movement of strontium and calcium between the circulating fluids and tissues. Values of $OR_{\text{body/diet}}$ of 0.2 to 0.5 have been reported for cattle, goats, sheep, and pigs (3). Thus, meat from animals consuming feed with the same Sr^{90}/Ca ratio as lactating animals would have about twice the Sr/Ca value present in milk. However, comparisons of Sr^{90} to Ca values of milk and meat from various survey studies in the United States show great variability, with meat values ranging from one-half to four times the milk values. This undoubtedly reflects differences in feed management of dairy and beef cattle.

Behavior of strontium and calcium in poultry has been studied experimentally in three-month-old cockerels on diets containing from 0.66 to 2.21 g of calcium per day, as well as in laying hens. The $OR_{\text{bone/diet}}$ values were the same, about 0.6 (68). From this, it can be inferred that with continuous feeding there would be an inverse relationship between dietary calcium level and radiostrontium retention under the conditions of the experiment. In other experiments the relative secretion of the two elements into the various parts of the egg was determined. The *OR* values for the egg yolk, egg shell, and femur were found to be about 0.6, whereas those for the plasma and egg white were much higher, about 1.5; the significance of the latter values is not understood. Further studies have been reported on factors affecting the transfer of Ca^{45} and Sr^{85} in the laying hen, but the difficulties of discontinuous administration techniques make interpretation difficult (69).

DIETARY CONSIDERATIONS

Recently there have been numerous reviews on various aspects of dietary radiocontamination: principles of biological availability (64, 70); levels and trends in the United States (13, 14, 71–74); compilation of data on a worldwide basis (3, 4, 75); survey studies (76, 77, 78); philosophy of radiation protection standards (16, Rept. No. 5; 79; 80; 81); problems from high levels of radioactivity (82).

In regard to the assessment of Sr^{90} in diets and food constituents, some general principles have emerged: (*a*) although levels in foodstuffs may fluctuate over short periods of time, it is more important to consider mean levels over longer periods, thus most data are reported on an annual basis; (*b*) the body burden of Sr^{90} to be attained depends primarily on the Sr^{90}/Ca ratio of the total diet; (*c*) the relative contributions of individual constituents of the diet do not depend on their Sr^{90} contents or even on their Sr^{90}/Ca ratios—the important factor is the effect that their inclusion in the diet has on the Sr^{90}/Ca ratio of the total diet.

The trends of Sr^{90} levels in the human diet can best be appreciated from values of milk, which has been the most studied item of food. The annual values (pCi Sr^{90}/g Ca) in milk from New York City from 1954 through the first half of 1964 were as follows: 1.4, 2.7, 3.9, 4.5, 7.6, 11.0, 8.0, 6.7, 12.1, 24.4, 23.9 (14); a value of 25 has been predicted for 1965 (16, Rept. No. 6). It can be noted that the levels decreased in 1960 and 1961, showing the effect of the test moratorium, and then increased again in 1962, showing the effect of resumed testing.

Values for total diets are given in Table III. There can be consistent geographical variations within countries; for example, values for San Francisco are generally lower than for Chicago or New York; this is attributed to rainfall differences, San Francisco foods being derived from so-called "dry" areas and the others from "wet" areas (16, Rept. No. 4). Also, food produced in local areas with particularly high rainfall and special agricultural conditions might have high values; in the United Kingdom it was reported that Sr^{90} concentration in milk from such areas was as high as eight times the country-wide mean (15). A detailed study has been made in arctic Alaska where special conditions are found; values for Sr^{90} apparently were not as greatly increased as for Cs^{137} (83). The Sr^{90}/Ca ratios of the total diets in Europe have been about the same as in the United States, as have the values reported for Japan despite the different composition of the diet. Values in the Southern Hemisphere as shown for Argentina and Australia have been consistently lower and showed little rise in 1962 and 1963.

Table IV shows the contributions of various foods to the total Sr^{90} of the diet for New York City in 1964. It is noted that milk and dairy products contributed about 54 per cent, and plant foods about 38 per cent of the Sr^{90} of the total diet. Recent experimental work has demonstrated that the Sr^{90} in wheat, and presumably in plant foods, is equally available to man as the Sr^{90} in milk (84). It is instructive to consider the effect of manipulation of diet composition. As an extreme example, using the data of Table IV, if a person obtained all of his calcium from dairy products, his dietary intake would be 26.8 pCi/g of Ca; on the other hand, if he obtained all of his calcium from plant foods, the level would be 38.7 pCi/g of Ca. Dairy products generally

TABLE III

STRONTIUM 90 IN TOTAL DIETS FROM DIFFERENT GEOGRAPHIC AREAS[a]

Country	Year			
	1961	1962	1963	1964[b]
	(pCi/g Ca)			
Australia	4.7	5.9		
Argentina			6.5	
Denmark	5.9	12.4	31.3	
France	9.2	16.9		
Japan	18.5	17.8	24.6	
United Kingdom	6.2	9.9	22.8	
United States				
New York	9.2	13.2	27.4	29.4
Chicago	6.7	10.5	17.9	25.4
San Francisco	3.4	5.3	12.2	15.3

[a] Refs. (4) and (14)—consumption values revised.

[b] January–June only.

TABLE IV

CONTRIBUTION OF DIET COMPONENTS TO TOTAL DIET STRONTIUM 90 (1964)[a,b]

	New York City			
	pCi/yr	Per cent	g Ca/yr	pCi/g Ca
Dairy products (milk)	6,386	53.9	238.2	26.8
Grain products	2,764	23.3	68.2	40.3
Leafy and other vegetables	1,003	8.5	23.4	42.9
Root vegetables	537	4.5	11.8	45.5
Fruits	260	2.2	14.6	17.8
Meat, fish, eggs	346	2.9	46.6	7.4
Water	549	4.6	—	—
Total	11,845			
Total g Ca/yr			402.8	
pCi/g Ca (total diet)				29.4

[a] Data compiled from Ref. (14), Vol. 155.

[b] January–June only.

contain a lower Sr^{90}/Ca ratio than do plant foods, because the cow always puts into milk less of the strontium than of the calcium that is in the ration. With time, after the cessation of nuclear testing as the fallout rate becomes low compared to the cumulative contribution, a situation will be approached in which the Sr^{90}/Ca ratio in milk is about one-tenth that in plant foods; this is demonstrated later (Table V) where the distribution of stable strontium is shown.

Infants' diets in the United States have been shown to have about the same Sr^{90}/Ca ratio as the average diet of adults. Few or no differences are seen in diets representative of teen-agers or adults of varying socio-economic groups. The Sr^{90}/Ca intake of breastfed babies is much lower than that of babies fed on cow's milk preparations because of the discrimination against Sr^{90} by the nursing mother (85, 86). Mineral preparations to supplement calcium are often prescribed for pregnant and lactating women; a series of products tested gave an average of 1.59 pCi Sr^{90}/g Ca at a time when milk values were about 8 (86). However, earlier tests showed that preparations using bone meal had comparatively much higher values (87).

METABOLIC BEHAVIOR IN MAN

Metabolic behavior in man can be described in general terms as follows (24, 88). After radiostrontium is ingested, part is absorbed from the gastrointestinal tract and part is excreted unabsorbed in the feces. That which is absorbed is: (*a*) deposited in the skeleton; (*b*) distributed in an exchangeable pool which can be considered as comprised of the plasma, extracellular fluid, soft tissue, and bone surfaces; or (*c*) removed from the body by urinary excretion and endogenous fecal excretion.

A model is presented (Table V) that summarizes present knowledge of the various discriminatory processes in terms of absolute amounts of stable strontium and calcium metabolized daily and present in the adult human being on a typical English diet (24, 89). This scheme is based on analytical values for stable strontium and calcium whenever available, and "Observed Ratios" from experimental studies when required; the original references should be consulted for explanations and qualifications. The numbers are slightly different from those in the original references because of differences in interpretation of data, but there is no substantial disagreement. From the standpoint of dietary contributions of Sr^{90}, Table V gives information on the situation that will be approached as fallout Sr^{90} reaches equilibrium with stable strontium in the biosphere. The various *OR* and *DF* values can be deduced from the Sr/Ca ratios given.

The $OR_{\text{body/diet}}$ (same as $OR_{\text{bone/diet}}$) is of practical importance. If the skeleton of an individual is formed entirely from a diet of given Sr^{90}/Ca ratio, then the concentration in the bone is equal to $OR_{\text{bone/diet}} \times Sr^{90}$/Ca of diet; under conditions of short-term exposure this quantity represents the theoretical maximum concentration in "hotspots." The actual concentration in

TABLE V

Typical Values for Amounts of Stable Strontium and Calcium Metabolized by Adult on English Diet (24, 89)

	Sr	Ca	Sr/Ca[a]
Dietary intake (mg/day)			
Dairy products	0.28	644	0.31
Plant sources	0.43	146	2.1
Meat, fish, eggs	0.18	69	1.9
Creta preparata	0.59	270	1.6
Water	0.19	60	2.3
Other sources		18	
Total	1.67	1207	1.0
Absorbed into body from diet (mg/day)	0.3	450	0.5
Endogenous secretion into feces (mg/day)	0.05	150	0.24
Unabsorbed in feces (mg/day)	1.37	757	1.3
Total in feces (mg/day)	1.42	907	1.2
Excreted in urine (mg/day)	0.29	250	0.84
Excreted in sweat (mg/day)	0.025	50	0.36
Plasma (mg)	0.12	350	0.24
Extracellular fluid (mg)	0.33	1000	0.24
Bone surfaces and soft tissue (mg)	1.2	3650	0.24
Bone (mg)	345	1.04×10^6	0.24
Newborn (mg)	5.6	2.8×10^4	0.14
Mother's milk (mg/day)	0.043	260	0.12
Accretion rate in bone (g/day)		0.5	
Half life in exchangeable pool (days)	2.4	3.7	
Half life in bone (days)	2300	2770	

[a] Value for total diet set at 1.0.

hotspots is generally lower than maximum because of the contribution of calcium from the body stores. An $OR_{\text{body/diet}}$ value of 0.25 has been generally accepted for adults; there is evidence from several groups that the value is between 0.8 and 1.0 at 0 to 3 months of age, falling to about 0.5 at about 1 year, and reaching the adult value of 0.25 sometime thereafter (4).

The rate of bone turnover strongly influences the deposition and retention of Sr^{90}. In infants and young children it has been estimated that about 50 per cent of bone mineral is replaced annually, with an almost complete replacement of skeletal mineral in the first 2 years of life (90). In older individuals, a gradation of replacement rates is thought to exist; for example, it is estimated that the replacement rate in adult long bones might be as low as 1 per cent per year as compared to a high of about 10 per cent in cancellous bones (4). The rate of elimination of radiostrontium from the body of man and animals has been studied and described by means of both successive exponential functions and power functions (91–94); the human data are limited, however, especially in regard to the influence of age and other factors. In a recent study with 3 subjects, starvation caused a loss of 1.1 pCi Sr^{90}/day from the body as compared to a retention of 0.1 during the control period (95). An excellent review has recently appeared on the adequacy for health physics purposes of the three concepts of strontium metabolism: the exponential model, the power function, and the *OR* approach (96).

The relative constancy of Sr/Ca relationships in man has suggested their use for monitoring body burdens or estimating dietary intakes. Controlled and population studies have indicated that the dietary Sr^{90}/Ca values can be reasonably well estimated for health physics purposes from measurements of Sr^{90}/Ca in urine (24, 97, 98); $OR_{\mathbf{urine/diet}}$ values in small and large groups of 0.47, 0.67, 0.75, and 0.84 have been reported as compared with the "standard" value of 0.84 in Table V. The $OR_{\mathbf{urine/diet}}$ value is known to be related to the dietary calcium (24). Values as low as 0.37 were found for individuals on a very low calcium intake and the suggestion made that the Sr^{90}/Ca ratio of stool is a better parameter (99). However, urinary measurements seem advantageous for ease of sampling and because they can reflect the Sr^{90} absorbed from the diet.

The feasibility of using children's teeth as an index of Sr^{90} accumulation and body burden during the time the teeth are formed has been demonstrated recently (100, 101). The suggestion has also been made that Sr^{90} in hair may be a useful index, but the relationships have not yet been worked out (102).

LEVELS IN MAN

Considerable data from various countries have been obtained and compiled on Sr^{90} levels in human bone (3, 4). There is a strong age and time dependency. In regard to age, highest values of Sr^{90}/Ca are observed in groups that include children aged 1 month to 2 years; still- and newborns have generally about one-half these values, primarily because of placental discrimination; in older groups the values decrease gradually, to level off at about 20 years of age, which is a reflection of the amount and degree of contamination of pre-existing bone. Time trends follow those of the diet or milk which in turn are governed by patterns of nuclear testing. As an example, values of pCi Sr^{90}/Ca in human bone from adults in New York City ranged from 0.83 in 1961 to 1.55 in 1963; values for the 1 month–2 year age group ranged from 3.43 to 9.84 (4). It is predicted that the bone values in the 0–4 year olds in 1965 will be about 8 pCi/g Ca in "wet" areas (as New York) and 4 in "dry" areas (16, Rept. No. 6). Detailed values for the United States for 1962–63 have been analyzed statistically and have shown a log-normal distribution (103). It has been useful to develop empirical relationships between the ratios of Sr^{90}/Ca in bone of infants and in the milk supplies (104). For the year 1962 the ratio of infant bone Sr^{90}/Ca to milk Sr^{90}/Ca for 9 countries ranged from 0.11 to 0.42 and averaged 0.24; a similar ratio for adult bone Sr^{90}/Ca to diet Sr^{90}/Ca in 5 countries ranged from 0.07 to 0.1 and averaged 0.09 (4).

CESIUM 137

Although Cs^{134} (2.07-year half life) and Cs^{136} (12.9-day half life) have been detected in man or his environment, only Cs^{137} (30-year half life) makes an appreciable contribution to the radiation dose to man (4). The principles governing Cs^{137} movement in the biosphere were reviewed in detail some time ago (105). Cesium and potassium are chemically similar. However, they are not metabolically interdependent and consideration of the two elements together does not offer the same advantages as for strontium and calcium. Nevertheless, Cs^{137} concentrations are often expressed in terms of potassium for two reasons: (*a*) naturally radioactive K^{40} and Cs^{137} are often measured simultaneously by gamma spectrometry, with the K^{40} thus serving as an internal standard; and (*b*) in man, the Cs/K ratio correlates better with lean body mass and hence with radiation dose than does the Cs^{137} per kilogram of body weight.

Because of the scarcity of data, the world-wide deposition of Cs^{137} is usually estimated by applying a Cs^{137}/Sr^{90} ratio to the values of global deposition of Sr^{90}. The half lives of Sr^{90} and Cs^{137} are so close that no changes in the Cs^{137}/Sr^{90} ratio, due to radioactive decay, are significant over a period of 10 years or less. The Cs^{137}/Sr^{90} ratios as they are produced vary between 1.0 and 3.0; the Cs^{137}/Sr^{90} ratio has been estimated as 1.7 in 1961 and as 1.5 for the period 1962 to 1963 (3). It must be remembered that this ratio will change markedly as the two elements pass through metabolic systems. The advantages and limitations of the use of the ratio pCi Sr^{90}/g Ca to pCi Cs^{137}/g K have been discussed (106, 107).

SOILS AND PLANTS

Cesium 137 appears to be less well absorbed from soil by plants than does Sr^{90}, primarily because of fixation in the lattice structures of clay minerals (2, 3, 48); see (108) for review of soil chemistry of Cs^{137}. In typical soils of temperate regions, Cs^{137} was absorbed about one tenth as much as Sr^{90}, although it must be remembered that relative absorption varies with soil type. With the passage of time, the absorption of Cs^{137} relative to Sr^{90} decreased and it is estimated that after 3 years the quantity of Cs^{137} absorbed may be about 1/25 or less that of Sr^{90} (3). In certain soils from tropical areas, however, Cs^{137} was found more available to plants than had been expected (3). Because of the limited availability for root absorption, it was expected that Cs^{137} levels in the food and in man would be correlated with the fallout rate. However, there have been some areas where milk concentrations of Cs^{137} have not followed the fallout rate, and it must be assumed that there is a mechanism for absorption of previously deposited Cs^{137}. It has been suggested that a high level of organic matter in the upper layer in the soil of some permanent pastures might reduce the binding of Cs^{137} by clays, thus prolonging its availability to plant roots (48, 109). The extent of fixation can be reduced by the use of stable cesium and, in some instances, by potassium.

The downward movement in undisturbed soil is much smaller for Cs^{137} than for Sr^{90}. After about 5 years, from 50 to 80 per cent of the Cs^{137} added to the soil surface may remain in the upper 5 cm, with little penetration below 10 cm (48, 110).

Cesium 137 enters plants by direct contamination in much the same way that Sr^{90} does and likewise is easily removed from the foliage by rain. However, Cs^{137} is readily redistributed within the plant, in contrast to Sr^{90}. Relationships between the deposition of Cs^{137} and its concentration in crops have been developed which are similar in principle to those shown in Table I (111).

AQUATIC FOOD CHAINS

Cesium 137 is concentrated in the flesh of aquatic organisms by a factor of 5 to 20 over that of the surrounding water (112). However, analyses of diets suggest that the contribution of Cs^{137} from fish is relatively small. Values for fish in 1961–63 from Finnish Lapland, which were expected to be high, ranged from 0.057 to 1.79 nanocuries per gram potassium (113). Methods for estimation of Cs^{137} in seawater have been recently reported and some values presented (114).

ANIMAL PRODUCTS

Cesium 137 is efficiently absorbed from the gastrointestinal tract for transport to muscle tissue and milk. In controlled experiments with the dairy cow, about 1.4 per cent of the daily ingested dose was secreted per liter of milk (115, 116; F. W. Lengemann, unpublished data); for the goat the value was much higher, about 9 per cent (see Eqs. 4 and 8 and Table II). The ratio of Cs^{137}/K in the milk to that in the diet was about 1.4 (117). Varying results have been reported from field trials but the reasons are not yet explained (118). Concentration in muscle tissue of cattle has been estimated at about 0.004 per cent of daily intake per gram and about 0.01–0.03 for sheep and pigs (115, 119, 120). Experiments have also been reported on deposition into eggs and tissues of poultry (68, 115, 120). The biological half-time in the cow, goat, pig, and hen has been estimated as about 20–30 days although some workers have reported a value of 2–3 days for the goat (115, 120); in any

TABLE VI

CONTRIBUTION OF DIET COMPONENTS TO CESIUM 137 IN TOTAL DIET (1964, yearly averages)[a,b]

	Consumed per day (g)	Cs^{137} intake per day (pCi)	Per cent
Dairy products (milk)	605	87	36
Grain products	265	84	35
Leafy and other vegetables	181	14	6
Root vegetables	170	4	2
Fruits	310	19	8
Meat, fish, eggs	315	33	13
Total	1846	241	

[a] Ref. (14), Vol. 146.

[b] Chicago data.

event, the turnover is rapid enough so that the tissue levels show little lag in following the dietary levels.

The retention of Cs^{137} in the body is affected by potassium and sodium levels as well as by diuretic action (121); however, the effects are relatively small and variable. The addition of 10 g of stable cesium daily to the diet of dairy cows had no effect on the amount of Cs^{137} secreted into the milk (F. W. Lengemann, unpublished data).

DIETARY CONSIDERATIONS

Average values in the United States for Cs^{137} in milk expressed as picocuries per liter from 1957 through the first half of 1964 are as follows: 34, 44, 54, 28, 10, 37, 117, 131 (2, 3). It is noted that Cs^{137} levels in milk in 1961 were slightly lower than in 1960, but rose sharply in the spring of 1962. Concentrations of this nuclide in milk have been related to phytoclimatic zones (122).

An example of contribution of various components to the diet is given in Table VI. It is of interest to note the relatively high contribution of grain products, about 35 per cent; in 1959 it was reported that the contributions to dietary Cs^{137} were: dairy products, 60 per cent; meat, 25 per cent; and grain, 7 per cent (105). In Denmark, Sweden, and England the contribution of meat has ranged from 20 to 50 per cent (4).

Considerable attention is now being given to the situation in some arctic regions where the Cs^{137} levels in food and man are 100 or more times greater than those in the northern temperate latitudes (4). This is primarily the result of accumulation of fallout on lichens and native vegetation which grows slowly and is grazed by reindeer and caribou; the local populations use meat from these animals as a large part of their diet. For example, for Lapland males from Finland a daily intake of 5000 pCi Cs^{137} was reported, of which meat contributed about 4330 pCi; this compares to a total daily intake in the United States of about 30 pCi (4).

METABOLIC BEHAVIOR IN MAN

Studies on cesium metabolism in man have recently been reviewed and analyzed (123). Cesium uptake from the gastrointestinal tract is rapid and essentially complete. Excretion is principally via the urine but with a continuing loss in the feces such that the urinary/fecal ratio ranges from 2 to 10 among individuals. Within the body, cesium is widely distributed, but mostly in the soft tissues. Cesium 137 has been found in bone at concentrations about the same as in muscle, although there are some Japanese data that require explanation; variations may result from effects of age and differing turnover rates among tissues.

The retention pattern of ingested cesium is required for estimates of radiation dose, and data have been reported from several laboratories. The whole-body retention of cesium has generally been expressed as a two-component exponential function; about 10 per cent of a single ingested dose is excreted with a half life of 1 to 2 days, and most if not all of the rest with a half life between 50 and 150 days. The variation is probably due to metabolic differences between individuals or to differences in diet. Limited evidence indicates that biological half lives in children of age up to 10 years are less than one third of the adult value (4). On this basis a working value of 100 days has been chosen as the biological half life of Cs^{137} in normal adults (4).

In studies with Finnish Lapps, relationships were established that permitted (under certain conditions) whole-body levels of Cs^{137} to be estimated from measurements on blood samples (124). In limited studies of secretion into human milk it was shown that the Cs^{137}/K ratio in milk was higher than that ratio in the diet and that about 30 per cent of the ingested Cs^{137} was secreted per liter of milk (125).

Tracer studies in animals have given additional information on cesium metabolism. In the rat about 98 per cent of ingested Cs^{137} was absorbed mainly within 30 min, with the small intestine being the most important site; about 25 per cent of Cs^{137} put into the bloodstream was removed by fecal endogenous excretion (126). Evidence was presented for the transfer of Cs^{137} from the serosal to mucosal side of an intestinal segment by a mechanism other than diffusion (127). The developing fetus of the rat was shown to come rapidly into equilibrium with the Cs^{137} in the maternal blood, the concentration of Cs^{137} in the fetal tissue being independent of fetal age or weight. The general distribution was the same in fetus and dam, but the Cs^{137}/K ratio was greater in the dam (128). The distribution of Cs^{137} in tissues of mice and dogs was determined after 400 days of chronic exposure; highest concentrations were found in muscle, with lower concentrations in fat, blood, skin, and bone.

Differences in whole bone concentration were due in part to the amount and state of the marrow (129). Behavior in dogs and direct measurements of Cs^{137} radiation dose to various tissues have been reported (130). The renal excretion of Cs^{137} has been increased in the rat by administration of carbonic anhydrase inhibitors (131).

LEVELS IN MAN

Values of Cs^{137} in man have been reported in detail (3, 4) and, unless otherwise noted, are expressed below as picocuries per gram of potassium. In the United States, levels in 1956 were about 50 and increased to a peak of about 70 in 1959; thereafter they fell to a low of about 20 in late 1961 and increased to about 45 in 1963. Levels in the Northern Hemisphere were generally similar except for subarctic regions and the coastal areas of Norway.

In various parts of Norway, values from 180 to about 1400 were reported for 1961 through 1963. In some groups of Finnish and Swedish Lapps the average levels reached, ranged from 470 to 4420 for 1961 through 1963; in early 1964 one group of Lapps reached an average of 7000. For individual reindeer breeders in the far north of the USSR, a range of 7140 to 25,700 was reported in 1964. In 1962 one group of Alaskan Eskimos had an average of 3000. During 1963 the highest average body burden of a group of Eskimos was found to be 628 nanocuries and generally there was about a 50 per cent increase over the 1962 values (132).

The frequency distribution of Cs^{137} has been estimated from measurements on 878 persons who died between 1959 and 1963; in contrast to previous estimates which predicted that 1 person per 50 million would have a body burden exceeding three times the mean, the recent work predicts 75,000 persons per 50 million (133).

IODINE 131

In addition to general references already cited, the published proceedings of a recent symposium on the biology of radioiodine summarizes aspects pertinent to the fallout problem (22). Iodine 131 (8-day half life) is the fallout radionuclide most likely to produce the greatest radiation exposures within short times (up to several weeks) after nuclear detonations. The relatively short half life has several important consequences: (*a*) I^{131} injected into the stratosphere almost completely disappears by radioactive decay before it can be returned to earth, and thus the primary source is tropospheric fallout; (*b*) I^{131} reaching the soil disappears by decay before it can be absorbed into growing plants and thereby transmitted to the food of man; (*c*) most I^{131} reaching the surfaces of plants that are consumed directly by man is removed mechanically or disappears because of transit time between contamination and consumption of the food; (*d*) fresh milk is the major contributor of environmental I^{131} to the human diet. Although there can be exposure by inhalation or consumption of unwashed fruits and vegetables, it is considered that these routes are of minor or local significance only.

Iodine 131 was generally detectable in the biosphere and man from 1951 through 1958, but during this period few data on its transport were obtained. The 1957 reactor accident at Windscale provided much information on relationships between I^{131} on grass and in milk; some studies have been made in the environs of large nuclear plants, but these findings may be limited in application. Most existing information is a consequence of the resumption of testing in 1961. Some recent papers deal with the important point that some of the I^{131} observed in the United States starting in the fall of 1961 originated from the selective escape of radioiodine from vented underground explosions at the Nevada test site (22, p. 43; 134, 135). There is controversy about the relative contributions from continental and other testing, but it seems clear that compared to usual tropospheric fallout a given amount of radioactivity released from a vented shot may have increased fallout significance because it can be deposited over limited areas.

Although the factors governing the retention of I^{131} on foliage could be of major importance, little work has been done on this aspect, presumably because of experimental difficulties (22, pp. 61 and 79). There are, however, two useful empirical observations: (*a*) from the Windscale accident it appears that an I^{131} deposition on grass of about 1 pCi/m^2 produces a concentration in milk of about 0.1 μCi/liter; and (*b*) there is an exponential physical removal of I^{131} from vegetation with a half life of about 14 days, thus giving an "effective half life" of I^{131} on vegetation or in animals grazing thereon of about 5 days. These matters have been reviewed and additional relationships developed between levels in milk, radiation dose to the thyroid, and open field external gamma dose rates (136, 137); this approach has many advantages, but extrapolations to past or future situations are difficult because of uncertainties in available data. Perhaps of most importance is that these calculations should place us on guard as to the possible future occurrence of high levels in local population groups.

SECRETION INTO MILK

The secretion of I^{131} into the milk of domestic animals is a primary factor in governing the exposure of the human population and therefore has been studied intensively (64, 116, 138, 139). Ingested I^{131} appears rapidly in the milk, and the peak concentration occurs less than one day after the ingestion of a single dose; the level then falls rapidly so that by the third to fourth day the I^{131} concentration is about one-tenth that at maximum. This has practical implications: (*a*) to prevent public consumption of milk contaminated by fallout, remedial action to be maximally effective must be taken within one or two days after contamination occurs; (*b*) if the cows are transferred to uncontaminated feed, the levels of I^{131} in milk will be effectively reduced within a few days.

Recent data have been reported on amounts of ingested I^{131} that are secreted into milk under single and chronic ingestion, the state of I^{131} in milk, and the partition of I^{131} in the cow (22, p. 151; 140–142). The behavior of I^{131} appears to be much more variable than that of Sr^{90} or Cs^{137}, being affected by such factors as breed and individual differences, milk production, season, and diet. The effects of chemicals, including thyroxine and stable iodine, on secretion of I^{131} into milk have been reviewed (64, 143). Under conditions of oral ingestion, about 8 per cent of the daily intake of I^{131} is secreted into each day's milk: values from 4 to 20 per cent have been observed. On the same pasture, the concentration in goat's milk is expected to be 5 to 10 times that in cow's milk. The quantitative aspects are summarized in Table II and Equations 5 and 9.

METABOLIC BEHAVIOR IN MAN

Reduced to simplest terms, the radiation exposure of the population to I^{131} is directly related to the (percentage of ingested I^{131} per gram of thyroid) $\times$(fresh milk consumption); the range of the various factors involved, such as age dependence, thyroid size, percent uptake, and biological turnover, have been reviewed (22, pp. 183, 187, 191, 201, 219; 64; 144). It appears that, as a combined effect of thyroid weight and fresh milk intake, the highest thyroidal depositions of fallout I^{131} would be expected in the 6 months to 2 years age group.

LEVELS IN MAN

Few data are available on levels of I^{131} in milk prior to 1959. After the I^{131} from the 1958 tests could no longer be detected, none was observed until the resumption of testing in 1961. In the United States a peak was reached around October 1961 (about 100 pCi/liter) and levels fell to detection limits in January 1962; levels started to rise in May 1962 and reached a peak in November (about 80 pCi/liter). Both in the autumn of 1961 and in the summer of 1962, average monthly values exceeding 700 pCi/liter were observed at some of the individual collection stations. Daily values were observed as high as 2000 pCi/liter for some stations, and it is possible that individual dairy herds within a station had maximum daily levels two to four times as great as the area average (13).

In Utah high levels of I^{131} in milk were observed in July 1962 as a result of testing in Nevada (145). From field observations it was determined that the total I^{131} intake of an individual consuming 1 liter of milk daily would be 12.8 times the peak I^{131} concentration; this is in good agreement with the value of 15 reported in Table II. On this basis an average total intake of I^{131} during this period was estimated at 58,000 pCi with a maximum of 800,000 pCi.

Country-wide integrated averages have been calculated as (picocuries of $I^{131}\times$days) per liter; in the United States these values for 1961 through 1963 were 8220, 10,820, and 1700, respectively (4).

Because of technical difficulties, only a limited number of direct measurements have been made of I^{131} in thyroid glands of humans and domestic animals. These data have in general agreed with expectations on the basis of known physiological behavior, milk levels, and milk consumption. Thyroid glands from young calves in Alabama during the period September 21, 1961, to January 11, 1962, showed a maximum daily average of 7300 pCi I^{131}/g of thyroid (146). The following results on human beings, expressed as picocuries of I^{131} in the thyroid, were obtained by *in vivo* counting methods during the period August–October 1962; Utah adults—700 to 11,000; Boston (4–17 years of age)—30 to 175; New York adults—300 (4).

CARBON 14

Carbon 14 (5700-year half life) has always been produced in the earth's atmosphere by the action of cosmic ray neutrons on nitrogen atoms; man-made C^{14} comes mainly from nuclear tests and depends upon the total rather than fission yield. Atmospheric C^{14} is almost exclusively in the form of carbon dioxide and is utilized by plants in photosynthesis to become incorporated in all living things. Little attention has been given to the movement of C^{14} in the food chain because the specific activity of C^{14} in the population simply reflects that of the atmospheric carbon dioxide from which it originates with a lag time of about a year (147). The relative rates of incorporation of atmospheric C^{14} in various human tissues have recently been studied (148); the soft tissues reflected the C^{14} content of the atmosphere as of several months earlier, whereas uptake into cartilage was much slower.

For purposes of predicting future levels of man-made C^{14} in the atmosphere, a four-compartment model has been proposed in which $N = C^{14}$ in units of atmospheric capacity and k = transfer coefficients in atmospheric units per year: stratosphere $(N=0.15,\ k=0.075) \rightleftharpoons$ troposphere $(N=1.5,\ k=0.27) \rightleftharpoons$ surface oceans $(N=1.5,\ k=0.082) \rightleftharpoons$ deep oceans $(N=60)$ (4). In this model biospheric carbon has been included in the atmospheric reservoir, and humus carbon with the deep oceans on the basis of similar transfer coefficients.

Before nuclear testing, the atmospheric content of C^{14} was about 40×10^{27} atoms and the specific activity of a standard wood (grown during 1890) was 14.5 disintegrations per minute per gram of carbon. In 1955 the specific activity of tropospheric carbon dioxide was a few per cent above the natural level, but in 1959 it had increased to about 30 per cent above; it is predicted that there will be a peak excess C^{14} activity in 1964 or 1965 of about 70 per cent with a fall to about 60 per cent in 7 or 8 years and then a progressive drop to about 3 per cent between 1970 and 2040, after which further decreases will come about only by radioactive decay (4).

OTHER RADIONUCLIDES

The metabolic behavior of Sr^{89} (50-day half life) is the same as described for Sr^{90}, providing the half life is taken into account. In the Northern Hemisphere the deposition of Sr^{89} in mCi/km^2 from 1961 through 1963 was 31, 95, and 63, respectively; in the Southern latitudes it was one-sixth to one-fifteenth these amounts (4). In the United States the yearly means of Sr^{89} in milk, expressed as pCi/g Ca for 1961 through 1963, were 9, 38, and 37, respectively; because of the short half life, the milk levels fell sharply by the end of 1963; annual diet levels were computed to be 44, 117, and 68 pCi Sr^{89}/g Ca for these three years.

The fallout rate of Sr^{89} has been used as an index of the amount of short-lived activity being deposited. In 1962 the ratios of annual deposits of the listed radionuclides as compared to Sr^{89} were as follows: Zr^{95}, 1.5; Ru^{103}, 1.4; Ru^{106}, 0.9; I^{131}, 1.1; Ba ^{140}, 1.3; Ce^{141}, 1.0; Ce^{144}, 1.5 (4). Whole-body counting of newborn, infants, and children in 1962–63 showed only traces of Zr^{95}, Nb^{95}, and Ru^{103,106}, whereas the Cs^{137} level reached 80 picocuries per kilogram body weight (149). Values for Ce^{144} and Cs^{137} have been reported for wheat grown in the United States in 1963 and found to be roughly similar, ranging from 90 to 780 pCi/g (150).

Tritium (12.5-year half life), which is naturally produced by cosmic rays, is also produced and released into the atmosphere by thermonuclear weapons. Before testing, the levels in rainwater were 1–10 tritium units; between 1953 and 1963, values have fluctuated around 100 tritium units in the Northern Hemisphere and around 5–20 in the Southern Hemisphere (4).

Beryllium 7 (54-day half life) has been detected in air and rain as produced from the 1961–62 tests (4). Other nuclides, either deliberately added to nuclear devices or produced by neutron activation, have been measured in the atmosphere or precipitation and used to study problems of meteorological circulation. These include W^{181} (145-day half life), W^{185} (74 days), Rh^{102} (210 days), Mn^{54} (310 days), Fe^{55} (980 days), Sb^{124} (60 days), Y^{88} (104 days), Co^{58} (72 days), Na^{22} (2.6 years), Pb^{210} (20 years), and Zn^{65} (245 days). The appearance of various gamma emitters in a fin whale has recently been reported (151). Plutonium isotopes from nuclear tests have been observed; atmospheric levels were presumably increased by the possible burnup of an isotopic nuclear power source for a space satellite (4). Levels of plutonium have been reported in diets, human tissues, and animal tissues (71, 152); experiments showed that following ingestion by a cow of a soluble form of plutonium, less than 10^{-6} per cent of the dose per liter was secreted into milk (153). There is no evidence of a significant contribution of these radionuclides to the radiation dose of humans.

CONCLUDING REMARKS

Understanding of the movement of radionuclides in the biosphere comes from two approaches: controlled metabolic studies and assessment of data from surveys. Controversy has frequently occurred when survey results have been improperly used to generate physiological and metabolic knowledge, and when arbitrary relationships useful for predictive purposes have been regarded and misused as fundamental biological properties. In most instances, however, the results of controlled and survey studies are eventually found to support and supplement each other.

There are related areas beyond the scope of this review to which increasing emphasis is being given: (*a*) the effects of environmental radiocontamination on the human population; (*b*) the development of appropriate protective or countermeasures; and (*c*) the setting of levels of environmental radioactivity at which such measures should be implemented. It is difficult, but necessary, to strike a balance between the risk of radiation exposure and the impact on the public well-being that any protective action might have (16, 81). Reduction of radiation exposure from world-wide fallout could only come about from large-scale changes in agricultural practice, food technology, or dietary habits. It appears to be agreed that present or foreseeable levels of widespread radiocontamination do not warrant such action. Official recommendations and measures for dealing with localized contamination have been established for I^{131} (16, Rept. No. 5) and are under consideration for Sr^{90}, Sr^{89}, and Cs^{137}.

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AIRBORNE RADIONUCLIDES AND PLANTS

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Whenever pollution increases the concentration of airborne radionuclides, deposition quickly increases the radionuclide burden in plants. The burden may become a hazard to human or animal health through introduction of radionuclides into foods. With extremely radioactive deposits, the growth of plants is also affected. In the more likely occurrences of contamination with concentrations of radionuclides little above natural background, the hazard to health and plant growth would probably be small.

The study of deposition and retention of airborne radionuclides on plants is significant for understanding the behavior of other types of airborne pollutants. The physical behavior of particles of given size is expected to be similar, whether they bear radionuclides or some other type of pollutant. Deposition and retention of real or simulated fallout particles and gases have been studied with various kinds of plants. Studies with airborne natural radionuclides indicate that similar principles govern their deposition and retention on plants.

The present review summarizes current information on the factors governing the deposition of radioactive materials from the air and their retention by plants. The nature of airborne radionuclides and mechanisms for their deposition on plants and removal from plants are described. Finally, the effects of various levels of contamination on plants are discussed.

Background Radiation

It is helpful, for an evaluation of hazard, to consider moderate or low levels of radioactive fallout against the background of natural radioactive elements in the environment. Crop plants normally contain measurable amounts of various radionuclides. The amounts found may vary considerably, depending on the crop and soil, but a reasonable calculation given by Hansen et al. (1960) is shown in Table 1. The calculation is for a heavy crop, 125 tons of green plant material on 1 hectare, containing 90% water, 4% carbon, 0.2% potassium, and commonly expected amounts of uranium and radium. Of these radionuclides, only tritium (hydrogen 3) and carbon 14 would enter plants predominantly from the atmosphere.

Table 1. Microcuries of natural occurring radionuclides in 1 hectare of green crop plant
Recalculated from Hansen et al., 1960

K^{40}	200	C^{14}	33	H^3	0.4
Rb^{87}	50	Ra^{226}	1	U^{238}	0.4

Menzel, R. G. 1967. Airborne radionuclides and plants. pp. 57-75. In: *Agriculture and the Quality of our Environment*. (N. C. Brady, ed.). American Association for the Advancement of Science, Washington D. C.

Similar values for the normal atmospheric burden of radionuclides, excluding any contribution from nuclear industry, are shown in Table 2. The units are microcuries per 10,000 cubic meters (1 meter-hectare) for easy comparison with Table 1. Radon and tritium concentrations in surface **air** are highly variable. The radon nuclides originate by decay of radium in the soil and diffuse into the atmosphere. The concentration in surface air not only depends on the radium content of the soil but also increases markedly when there is little turbulence (Burton and Stewart, 1960; Jacobi and André, 1963). The tritium content varies mainly according to the content of water vapor in the air (Kaufman and Libby, 1954). The amount of radionuclides, in terms of microcuries, is considerably greater in 1 hectare of green plant than in 1 meter-hectare of surface air.

Table 2. Microcuries of naturally occurring radionuclides in 10,000 cubic meters of air

Summarized from data by Anderson and Libby (1951); Burton and Stewart (1960); Jacobi and André (1963); Kaufman and Libby (1954); Peirson (1963); and Schumann and Stoeppler (1963).

		Pb^{212}	0.03	Be^{7}	0.0004
Rn^{222*}	0.5-10	C^{14}	0.01	Pb^{210}	0.00003
Rn^{220*}	0.5-10	H^{3}	0.0002-0.005	Po^{210}	0.000004

* The short-lived daughters of radon have been omitted from this table, although they are present at roughly the same concentrations as the parent nuclides.

The extent of fission-product contamination in the past is illustrated by observations made in 1958 after atmospheric testing by the United Kingdom, Russia, and the United States. Alfalfa samples collected in South Dakota, Nebraska, Minnesota, and Indiana during this period were analyzed by the U. S. Food and Drug Administration (1960). The total beta activity (excluding potassium 40) averaged about 10,000 picocuries per kilogram dry weight, or about 250 microcuries per hectare if one assumes 2.5 tons dry weight, a reasonable yield for alfalfa. The corresponding concentration of fission products in air may be estimated from the concentrations observed at three stations of the Public Health Service Radiation Surveillance Network located in these same states. During the two months preceding harvest of these alfalfa samples, the gross beta concentrations in the air (excluding tritium, carbon 14, and radon and its short-lived daughters) averaged about 0.04 microcurie per 10,000 cubic meters (U. S. Public Health Service Radiation Surveillance Network, 1960). In this example, the radioactivity of fission products deposited on alfalfa was probably greater than that of naturally occurring radionuclides in alfalfa, even though the radioactivity of fission products in the air was considerably less than that of naturally occurring radionuclides in the air.

A small portion of the beta activity in alfalfa could have been taken up from the accumulated fallout contamination in the soil; it would consist primarily of radioactive strontium (Frere et al., 1963). It has been shown that, even for radiostrontium, the amount deposited from the atmosphere in 1958 was considerably more important in the contamination of pastures at that time than the amount taken up from soil (Kulp, 1965). The importance of airborne radionuclides for contamination of plants is evident from this example.

Nature of Airborne Radionuclides

Most airborne radionuclides are associated with particles, which may have been introduced into the atmosphere along with the radionuclide or which may already be present from other sources. Nuclear explosions near the ground surface give rise to radioactive particles with diameters ranging up to several millimeters. Such large particles fall out close to the explosion site, but particles less than 100 microns in diameter may be carried hundreds of miles in the atmosphere after megaton explosions (U. S. Atomic Energy Commission, 1962). Particles 5 microns in diameter have been observed thousands of miles from the site of megaton explosions (Sisefsky, 1961). Radioactive fission products are incorporated into the particles as they solidify from molten or gaseous matter raised up in the explosion. Some of the more volatile fission products, or those derived by decay of a volatile fission product, such as strontium 90, tend to adsorb on surfaces of particles after they solidify (Klement, 1965).

The naturally occurring, nonvolatile, radioactive daughter products of radon become associated with submicron dust particles normally present in surface air. In observations at Washington, D. C., in late 1964 by Lockhart et al. (1965)., ground-level air was passed successively through a series of increasingly fine filters. The size distribution of radioactive particles was deduced from the relative amounts of radioactivity collected on the various filters. The radon daughter products, short-lived lead 214 and bismuth 214, as well as long-lived lead 210, were associated primarily with particles less than 0.3 micron in diameter. Fission products from the stratospheric source of old bomb debris were associated with particles averaging between 0.5 and 1 micron in diameter. Short-lived fission products from the Chinese atomic test of October 16, 1964, were associated with a somewhat larger average particle size group than the older fission products.

If the radionuclides are soluble, they may react chemically with other components of the atmosphere. A high solubility would also favor absorption into plant tissues after particles had been deposited on plant surfaces. Most of the radioactive fission products in bomb debris are very sparingly soluble in water (Lindsten et al., 1961). However, more than half of the strontium 90 in such debris may dissolve in water, depending on the immediate environment of the bomb (Bryant et al., 1960).

Radioactive gases in the atmosphere include water vapor, carbon dioxide, radon 222, radon 220, and some radioactive fission products. The radon nuclides and their short-lived daughters are the most abundant naturally occurring radionuclides, in terms of number of radioactive disintegrations, in the atmosphere. Krypton 85 is produced in nuclear explosions and escapes in reprocessing of spent nuclear fuels. The concentration of krypton 85 was about 0.07 microcurie per 10,000 cubic meters of air in 1962 (Ehhalt et al., 1963) and may be expected to increase considerably as nuclear fuel is more widely used. Less than 30% of the iodine 131 in fallout from Russian nuclear explosions was found in the gaseous form in England in 1961 (Peirson and Keane, 1962), the remainder being attached to particulate debris. Somewhat more gaseous iodine would be expected, according to aerosol chamber studies of radioiodine adsorption on particles (Clough et at., 1965). About half of the radioiodine in stack effluents from Hanford is in the form of gaseous alkyl iodines, which show less tendency to wash out of the atmosphere with condensing water vapor than gaseous elemental iodine does (Engelmann and Perkins, 1966).

Atmospheric testing of thermonuclear weapons produced large quantities of tritium and carbon 14 in the period from 1952 to 1962. The amount of tritium in rain increased to a maximum in 1963 of about 1000 times the amount of naturally produced tritium (Thatcher et al., 1965). The peak content of carbon 14 in surface air was also reached in 1963 at about twice the normal content (Young et al., 1965).

Attention must therefore be directed toward evaluating the accumulation of radioactive particles and gases on plant surfaces. The particles may range from about 0.1 to 100 microns in diameter. The larger sizes are generally associated with higher levels of radiation from fallout closer to a nuclear explosion. Submicron particles are associated with worldwide fallout and with some important natural radionuclides. The radioacitve gases include water vapor and carbon dioxide, whose relationships to plants are vital for crop production.

Mechanisms of Deposition

Important mechanisms of deposition of radionuclides on plant surfaces include rainfall scavenging, gravitational settling, impaction, eddy turbulence, and diffusion. Rainfall scavenging is probably most important for particles smaller than 10 microns in diameter. In general, gravitational settling and impaction are most important for particles larger than about 10 microns in diameter. Eddy turbulence and diffusion are important in the transport of gases to plant surfaces. The mechanisms of particle deposition, as applied to spores, have been thoroughly discussed by Gregory (1961).

Rainfall scavenging is the dominant mechanism for deposition of worldwide fallout (Martell, 1959). The estimated fraction of strontium 90 deposited by rainfall ranged from 50 to 90% at five sites in Clallam County, Washington, where the mean annual rainfall ranges from 15 to 110 inches (Hardy and Alexander, 1962). In the arid regions of Mohave County and Yuma, Arizona, where the total rainfall in 10 years was 34 and 20 inches, respectively, the strontium 90 deposited by rain was estimated to be roughly equal to that deposited by dry mechanisms (Meyer and Alexander, 1965). Rainfall scavenging should be equally effective for natural airborne radionuclides that are carried on small particles.

The importance of rainfall in contaminating several crops grown in Florida in 1962 is shown in Figure 1 (Menzel et al., 1963). Approximately 90% of the strontium 90 content of the crops resulted from intercepted rainfall.

The efficiency of rainfall scavenging is also high for particles larger than 10 microns in diameter (Greenfield, 1957). Such large particles, however, are likely to settle by gravity before rainfall occurs.

In the absence of rainfall, the deposition behavior of different radionuclides has been compared by calculating the deposition velocity (Peirson and Keane, 1962), defined as

$$v_g \ (\text{cm sec}^{-1}) = \frac{\text{Rate of deposition (pc cm}^{-2}\text{ sec}^{-1})}{\text{Concentration in air (pc cm}^{-3})}$$

The ground area, not the leaf surface area, was considered in this calculation. The observed v_g on vegetation may vary according to the percentage of ground cover and other characteristics of the vegetation. Deposition velocities as measured on grass cover under dry conditions are shown in Figure 2 (Chamberlain, 1966b).

For large particles, spores 19 or 32 microns in diameter, v_g in still air is equal to the terminal velocity of gravitational settling. With increasing windspeed, impaction of particles on leaf surfaces increases v_g severalfold (Chamberlain, 1966b). The stickiness of the surface is important in determining initial retention of impacted particles. However, once deposited on the surface, the spores show little tendency to be blown off. Gravitational settling contributes relatively less to the observed deposition velocity of particles in the 1- to 5-micron size range.

The deposition of submicron particles on plant surfaces is not as well understood (Chamberlain, 1966b). This is a matter of importance, because most airborne radionuclides are normally carried on particles in this size range and v_g is much greater than can be accounted for by settling. A boundary layer of still air exists within a fraction of a millimeter of the plant surface. Particles may impact on the surface with momentum gained by eddy turbulence outside the boundary layer may be important in trapping particles. Effects of electrostatic charge on the particle and on the plant surface do not seem to have been adequately investigated.

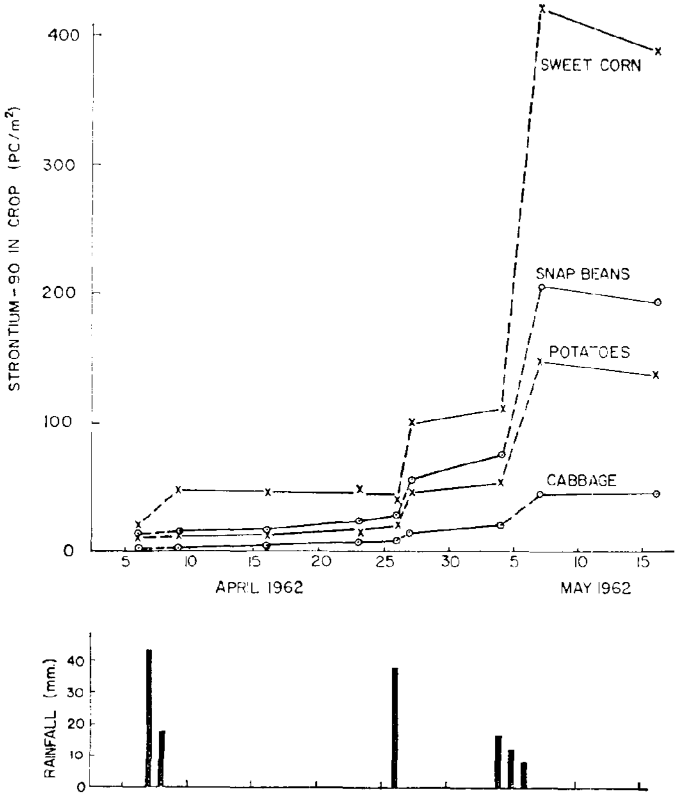

Figure 1. Strontium 90 content in four crops grown at Belle Glade, Florida, in relation to date and amount of rainfall (from Menzel et al., 1963).

For gases, the observed v_g varies with windspeed in a manner suggesting that eddy turbulence and molecular diffusion are controlling mechanisms (Chamberlain, 1966a). Physiological conditions in the plant may also affect the observed v_g (Barry and Chamberlain, 1963), since v_g reflects net accumulation, i.e. deposition less release. Lead 212 in vapor form is absorbed on external plant surfaces without appreciable release. Its deposition velocity lies in the range of 1 to 10 cm sec^{-1}. The deposition velocities for iodine, carbon dioxide, or water vapor are lower. For example, the deposition velocity of iodine on bean leaves, related to that of lead 212, was about 0.5 cm sec^{-1} in

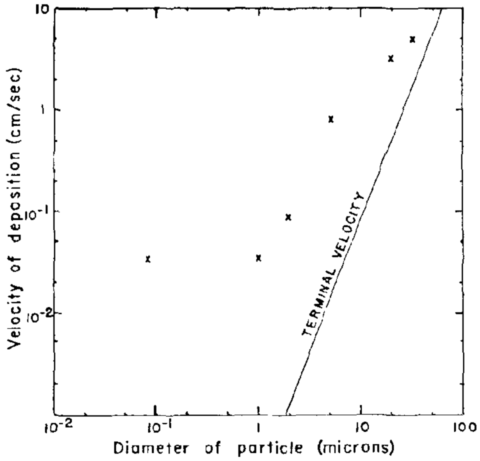

Figure 2. Deposition velocity of various types and sizes of particles on grass (from Chamberlain, 1966*b*).

humid air and 0.05 in dry air (Barry and Chamberlain, 1963). Presumably, the leaf stomata were more open in humid air (>90% relative humidity) than in dry air (<15% relative humidity).

The assimilation of carbon dioxide by crops may be expressed in terms of deposition velocity. The assimilation rate during high photosynthetic activity approaches 500 kg of carbon dioxide per hectare daily (de Wit, 1965). Taking the carbon dioxide concentration of air as 3 kg per 10,000 cubic meters, v_g is found to be 0.2 cm sec^{-1}. The assimilation rate is higher during the day than at night, so that under some conditions v_g for carbon dioxide may approach that found experimentally for lead 212 vapor.

Mechanisms for deposition of airborne radionuclides on plants depend on the size of particle with which the radionuclide is associated. Most of the worldwide fallout and natural airborne radioactivity is deposited on plant and soil surfaces in rainfall. In the absence of rainfall, large particles are deposited by gravity and impaction. Smaller particles are deposited more effectively than can be accounted for by gravity and impaction, but the mechanisms are not clear. Deposition velocities observed for gases are complicated by concurrent release. When there is little or no release, the deposition velocity is about equal to that for particles 30 microns in diameter, and greater than that for smaller particles.

Retention by Plants

Some radioactive particles, after deposition on plants, are dislodged more or less readily, whereas others are very difficult to remove. Movement of plant parts by wind or passing animals causes visible loss of large particles. The washing action of rain removes additional particles. Losses are also caused by the dropping of some plant parts and by the volatility of gaseous radionuclides.

The removal processes may be significant even during deposition of radionuclides. In a study of ash fallout from the Irazú volcano (Stanford Research Institute, 1966) in Costa Rica, initial retention of particles was roughly twice as great on damp foliage as on dry foliage. The particles observed in the study were considered representative of those likely to occur in close-in fallout from nuclear explosions. They ranged in diameter from 10 to 500 microns, median diameters at different sampling locations ranging from 50 to 100 microns. Presumably, the difference in initial retention was caused by loss of particles from the dry leaves.

The volcanic fallout particles that were retained on plants had nearly the same particle size distribution as those deposited in tray collectors. This was true even after some particles had been lost from the plants by one or two days' exposure to weather after the fallout. In contrast, Romney et al. (1963) found that few fallout particles larger than 44 microns in diameter were retained on foliage after several days in the Nevada desert. Windier and drier conditions, as well as longer exposure, in the desert probably account for the difference in retention of large particles.

Smaller particles are apparently more difficult to remove, but quantitative information with particles of known size is very scarce. Of particles averaging 28 microns in diameter on rye, somewhat less than half were removed with 0.75 inch of water applied in one sprinkler irrigation (Menzel et al., 1961).

The loss of soluble materials that have dried on a leaf surface is slower, but still appreciable. Measured losses have ranged up to 90% in 28 days for several radionuclides on cabbage leaves (Russell, 1965). The loss varies with species and growing conditions, and may be partially accounted for by loss of wax particles from the leaf surface (Moorby and Squire, 1963).

Volatilization is thought to account for part of the loss of radioiodine from vegetation, although experimental evidence is inconsistent (Martin, 1963). The "effective half-life" of iodine 131 contamination on vegetation has been measured at 5.5 (Martin, 1963) and 3.5 days (Hawley et al., 1964). Since the "effective half-life" combines the radioactive half-life and the half-life of physical loss according to the relationship

$$1/t_e = (1/t_r) + (1/t_p)$$

the corresponding half-times of physical loss are 18 or 6 days, respectively. If volatilization actually accounts for much iodine loss, the rate of loss would probably vary greatly with temperature and windspeed.

Knowledge about the rates of removal of radionuclides from plant surfaces is very incomplete. It has been difficult to draw conclusions about the rates of removal of large particles, even from the voluminous data obtained with Irazú volcanic ash (Stanford Research Institute, 1966). Rainfall certainly plays an important role in removal of both particles and soluble materials. But it also increases deposition in the presence of airborne radionuclides, so that its role in removal is difficult to determine. The concept of half-time of physical loss may be useful as a rough generalization in the study of radionuclide removal from plant surfaces. It is doubtful, though, that the concept applies in detail because of the probably sporadic nature of the important processes of removal.

Levels of Contamination

High levels of radioactivity in the atmosphere are unlikely except in the event of nuclear explosions or accidents. If an explosion or accident produced contaminated particles larger than about 10 microns in diameter, they would fall out rather quickly, contaminating vegetation relatively close to the site of explosion or accident. Smaller particles would be deposited over a wider area and would thus tend to give lower levels of contamination. However, the occurrence of rainfall in the presence of radioactive particles might rise the level of contamination on vegetation by a factor of 10.

Airborne fission product concentrations have been measured on a routine basis since 1956 by the U. S. Public Health Service Radiation Surveillance Network (1960). Since that time the highest monthly average fission product concentration was 3.35 microcuries per 10,000 cubic meters of air, observed at Salt Lake City, in September 1957, during a series of test nuclear explosions in Nevada. If the same relationship held between concentration of radionuclides in alfalfa and air as that observed in 1958, the total beta activity in alfalfa would have been about 2 millicuries per hectare, or 0.8 microcurie per kilogram dry weight. This estimate is probably too high, since the radioactive half-life of fallout at Salt Lake City in September 1957 was probably shorter than that of fallout in the Midwest in 1958. During most of 1965 and 1966, the concentration of airborne fission products was little more than the detection limit of 0.001 microcurie per 10,000 cubic meters of air.

The levels of naturally occurring radon daughters on vegetation may be estimated from data already presented in this paper. The significant daughters are lead 214, lead 212, lead 210, and polonium 210. It is assumed that the deposition velocity (v_g) for particles of 0.2-micron diameter is 0.2 cm sec^{-1}. This value is derived from Chamberlain's data (1966b) using an average windspeed of 10 miles per hour. Concentrations (c) of the radon daughters in the air are taken from Table 2. Using the decay constant (λ) for each radon daughter, the rate of accumulation on vegetation will be

$$dn/dt = cv_g - \lambda n$$

The calculated values for accumulation in 6 weeks are shown in Table 3.

Table 3. Estimated deposit, in microcuries per nuclide, of airborne radon daughters on 1 hectare of green crop plant Calculated for 6-week period excluding deposition by rainfall scavenging.

Pb^{214}	5	Pb^{210}	0.2
Pb^{212}	3	Po^{210}	0.03

The values in Table 3 do not include deposition by rainfall scavenging, which may be 10-fold higher than the deposition by dry mechanisms. The short-lived lead 214 and lead 212 ($t_{1/2}$ = 26.8 minutes and 10.6 hours, respectively) deposited on plants by rainfall would quickly return to the level supported by the concentration in air. The long-lived lead 210 and polonium 210 ($t_{1/2}$ = 22 years and 138 days, respectively) might accumulate to levels 10-fold greater than shown in Table 3. No correction has been made for physical losses of lead 210 and polonium 210 from the plants, but they are probably small in comparison with other uncertainties in the calculation.

There are few reports on quantities of radon daughters in plants. Measured quantities of polonium 210 in aged tobacco leaf range from 0.1 to 1 picocurie per gram (Berger et al., 1965; Gregory, 1965; Tso et al., 1966). Because of the age of leaf and radioactive decay of polonium 210, the presence of slightly higher amounts of lead 210 at harvest is required. Assuming a yield of 1500 kg of cured leaf per hectare, the quantities of lead 210 per hectare are 0.15 to 1.5 microcuries. Thus, dry deposition mechanisms and rainfall scavenging of lead 210 from the atmosphere could account for a substantial portion of the amount present in tobacco leaf. Sometimes, however, the major portion probably arises from uptake of lead 210 from the soil.

Semiquantitative measurements (Johnson et al., 1966) have shown that lead 212 is present in freshly harvested forage in a somewhat greater amount than that calculated in Table 3. An unknown part of the lead 212 may have been deposited by rainfall scavenging, since no information is given regarding rainfall before harvest, but the conclusion that no significant part could have been taken up from the soil is based on the failure to detect lead 210 or radium 226 in the forage. Any uptake of lead 212 would be accompanied by uptake of lead 210, which is present in comparable amounts in soils (Talibudeen, 1964). Since lead 210 shows no appreciable radioactive decay during the life of the plant, whereas lead 212 decays almost completely in a few days, similar rates of uptake would lead to a much higher concentration of lead 210 than of lead 212 in harvested forage. Similar reasoning regarding radium 224 and radium 226 eliminates the possibility that lead 212 in the forage is a decay product of radium 224 that might have been taken up from the soil.

Although no measurement of lead 214 on plants has been reported, it should be readily observable by gamma spectroscopy on samples counted within an hour after collection.

Levels of radionuclide contamination on plants may vary greatly in the presence of fallout or other types of radionuclide contamination. The background of naturally occurring radionuclides in a heavy growth of plants amounts to roughly 300 microcuries per hectare. Fission-product contamination in crops in some areas during test nuclear explosions may have reached 2 millicuries per hectare. In the hypothetical case of a 5-megaton nuclear explosion on the ground, fission-product contamination might exceed 50,000 curies of gamma-emitting radionuclides per hectare for several hours after the explosion (U. S. Atomic Energy Commission, 1962). This value, corresponding to a gamma radiation level of 100 roentgens per hour, was derived for a location 35 miles downwind from the explosion. The level of contamination with beta-emitting nuclides would be higher, because all fission products emit beta rays but not all emit gamma rays.

Effects Upon Plants and Their Utilization

The observable effects of radiation upon plants range from the production of mutations at low dose rates to complete growth inhibition and death at high dose rates. Mericle and Mericle (1965) found more floral abnormalities and increased somatic mutation rates in Tradescantia at dose rate of 0.006 roentgen per day than at 0.001 roentgen per day. Both dose rates are close to that from normal background radiation. Observable growth inhibition requires much higher dose rates. With pine, a plant species relatively sensitive to radiation, needle growth on seedlings was slightly inhibited at 20 roentgens per day (Miller, 1965). More noticeable effects upon plant growth are likely at dose rates greater than 100 roentgens per day.

At high dose rates, the effects upon plant growth are similar, whether the dose arises from beta or gamma radiation (Menzel, 1965). Gamma dose rates higher than 100 roentgens per day are expected to extend several hundred miles downwind from a megaton nuclear explosion (U. S. Atomic Energy Commission, 1962). The beta dose rate from fallout particles, though several times greater than the gamma dose rate, is usually unimportant because of the short range of beta radiation. If a large percentage of particles remain in contact with plant surfaces, as they did under damp conditions in the study with volcanic fallout particles (Stanford Research Institute, 1966), the beta dose could add importantly to the total dose received by plants.

In addition to the effects upon plants themselves, deposition of radionuclides on plants may affect their utilization for human food. This aspect of contamination with radioactive fallout has received much attention in the past 10 years. The transmission of iodine 131, strontium 89, strontium 90, and cesium 137 from pastures through milk to the human diet is of major importance. Protective action guides applying to each of these radionuclides have been developed by the Federal Radiation Council (1964, 1965). Guidance is based on projected radiation dosages to critical body organs.

It is calculated, for example, that a concentration of 0.1 microcurie of either iodine 131 or strontium 90 per liter of milk might justify protective action in a situation where the contamination was deposited quickly. Observations in England (Peirson and Keane, 1962) and Nevada (Knapp, 1963) indicate that the corresponding level of iodine 131 on pasture vegetation is about 10 millicuries per hectare. A calculation based on the observed ratios of strontium 90 and calcium in cow's milk and diet (Comar and Wasserman, 1960) indicates that the corresponding level of strontium 90 is also about 10 millicuries per hectare.

In a mixed fission-product contamination, other radionuclides that are not readily transferred to milk would make up the bulk of the contamination. Exact percentages of iodine 131 and strontium 90 would vary with the age of the fission products and with fractionation of the nuclides during particle condensation. The percentage of iodine 131 in unfractionated fission products would be highest at 10 to 15 days of age, when about 7% of the total radioactivity would be contributed by iodine 131 (Hunter and Ballou, 1951). In the same fission-product mixture, the radioactivity of strontium 90 would be about 0.04% of the total. Mixed fission-product contamination could thus possibly justify protective action against iodine 131 if the level of contamination reached 150 millicuries per acre.

Radionuclides that have been deposited on plants may affect their growth and utilization. Effects upon growth probably occur even at background levels of a few tenths of a millicurie per hectare, but they are difficult to observe. Most of the background radionuclide content of plants is due to potassium 40 taken up from soil, but there is a small contribution from deposit of airborne radionuclides. Fission-product contamination, mainly from airborne radionuclides, may have reached 2 millicuries per hectare without any obvious effects on plant growth. With 150 millicuries of fission products per hectare, or less, if the contamination consisted mainly of radioiodine or radiostrontium, protective actions affecting utilization of the crops might be taken. If contamination reaches a few thousand curies per hectare, severe growth inhibition would be expected in some plant species.

Summary

Airborne radionuclides readily contaminate plant surfaces. In the presence of airborne fission products at a relatively low level, for example, the amount of radioactivity deposited on plant surfaces may exceed the radioactivity of elements normally present in the plants.

Most of the fission products and naturally radioactive elements in the air are carried on solid particles. In highly contaminated zones close to a nuclear explosion, the particles might be relatively large, from 1 micron to several hundred microns in diameter. Worldwide fallout and natural radioactivity are associated with smaller particles, from a 0.1 to 1 micron in diameter. Important gaseous radionuclides include naturally occurring carbon 14 as carbon dioxide, hydrogen 3 as water vapor, and fission-product iodine 131.

Rainfall is very important in the deposition and removal of radioactive particles from plants. The dominating mechanisms for dry deposition are gravitational settling for large particles and eddy turbulence and diffusion for gases. Mechanisms for deposition of the important submicron particles are not well understood. Further study of the deposition and removal of submicron particles from plants might be very helpful in suggesting ways to minimize levels of contamination in plants.

Radiation damage in plants is exceedingly difficult to detect except at levels of contamination thousands of times higher than those attained with worldwide fallout. The avoidance of unnecessary radiation exposure through transfer of radionuclides to human diet is, however, of direct interest to everyone.

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THE EXTENT AND SIGNIFICANCE OF SOIL CONTAMINATION WITH RADIONUCLIDES

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In November 1965, the White House issued a report (President's Science Advisory Committee, Environmental Pollution Panel, 1965) of a panel chaired by John W. Tukey, of Princeton University. We shall follow the practice of referring to it as the Tukey Report. This 317-page document puts relatively little emphasis on radioactive materials as a source of pollution of our environment. None of the subject matter panels was specifically addressed to the subject. Of the several subpanel reports, that on soil contamination is the only one having a section specifically labeled and devoted to radionuclides, and this section is slightly more than 1 page of the 16 pages of that subpanel's report. Another recent report (NAS-NRC, 1966a), prepared by the Committee of Pollution of the National Academy of Sciences-National Research Council, also puts relatively little emphasis on radionuclides.

We think that the degree of emphasis given in the Tukey Report to radioactive materials reflects approximately the current relative importance of these materials, in comparison with the others considered in the report, as a potential threat to the quality of our environment and to human health. At the same time, however, dealing with radioactivity offers both similarities and contrasts to the problems of chemical and biological pollution. The experience thus far gained in the study of radioactivity in the environment can probably be applied with profit to these other problems. The following will illustrate what we mean.

The Tukey Report panel on soil contamination notes that about 200 isotopes of 35 elements have been identified from nuclear explosions and fallout but that many of them are not important, for any of three reasons: (1) small amounts are involved; (2) half-lives are extremely short; and (3) the isotopes are not incorporated into the food chain. With respect to reason 1, the small amounts of radioactive materials, much controversy has existed over how small is "small," in terms of biological hazard. The controversy has for the most part omitted noting that its very existence depends upon methods of measurement that permit the counting of mere hundreds of atoms in a sample. A reasonable lower limit of detection of strontium 90 in a 1-kilogram soil sample in which 1 disintegration per minute can be detected is equivalent to about 3×10^{-12} part per million of soil. Shorter-lived radon 222 in an air sample can be detected down to approximately 350 atoms per liter of air, or about 10^{-16} part per million. The last twenty years have seen emphasis put on more sensitive and precise methods of measurement. It is a common finding that combinations of chemical pretreatment and low-level counting or gamma spectrometry give the best precision and sensitivity leading to the low limits of detection such as just discussed. On the other hand, if one wishes to suppose that any amount of radiation exposure, hence any quantity of radioactive material, is

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potentially harmful biologically, he will be concerned with potential harm at levels of radioactivity below detection.

With respect to reason 2, half-life, the property of radioactive decay, is, of course, unique to radioactive materials. All radioactive substances do decay, but the rate at which decay occurs determines the applicability and choice of control measures if needed. The rate is independent of the chemical form of the substances, so that residual contamination from short-lived nuclides is usually allowed to decay to nonradioactive forms without human control or intervention.

With respect to reason 3, which concerns incorporation into the human food chain, the extent depends on the ordinary physical and chemical properties of the element itself, and of the radioactive residues, as for other contaminants. Of course, the forms of fallout particles are quite different from those of other materials--organic pesticides, for instance.

The fact that the property of radioactive decay is independent of the ordinary chemical properties of materials has meant that the chemical and biological behavior of the newly introduced radioactive materials can be studied in relation to existing chemical and biological knowledge, especially knowledge pertaining to trace elements in the geosphere and biosphere. Curiously enough, this very independence of the fundamental property of radioactive decay has led to a scheme, which can be referred to as the "limiting specific activity," for estimating the hazard of radioactive materials released to the environment. Under this scheme, the quantity of a radionuclide released to the environment is compared with the quantity of the same element already present in the environment (for example, strontium 90 is compared with stable strontium), and it is asserted that the specific activity (curies of strontium 90 per gram of stable strontium) will not increase over the initial value. The argument seems tenuous to us because the chemical forms of the radioactive and stable isotopes are not necessarily alike, and it is not clear that when they differ the stable form will always be the more available.

A broader problem, common to radioactive and nonradioactive materials alike, is referred to by the pesticide experts as "magnification" and by the radioactivity experts as "concentration." That is, quantities of a contaminant per unit weight of material in the environment, specifically in living tissues, may increase above the initial values, depending on the physical, chemical, and biological processes involved. For example, some marine organisms concentrate zinc 65 or iron 55 enormously. Dilution or degradation processes cannot be assumed to be universal.

Some radionuclides exist in the environment naturally. The present radionuclide composition of the environment is, of course, not the same as the old steady-state composition; the man-made additions have led to transient radiation exposure conditions. Both these facts have made it difficult to estimate what the new radiation fields and radioactive materials in the natural environment provides a potential measuring stick to appraise the extent and significance of the man-made sources of radioactivity. In the human species, at least, biological response to changes in environmental exposure conditions - for example, genetic steady state - has undoubtedly not been reached either, and this limits the usefulness of the measuring stick.

We do not believe that quantities of radioactive contaminants in the environment can be compared usefully with those of nonradioactive contaminants. Most of the mass of a fallout particle, for example, is radioactively inert, and we doubt that, as a general approach, a comparison of biological toxicities would be of great value either. For the most part the big decisions about the quality of the environment do not include direct tradeoffs between releasing radioactive materials and releasing other contaminants. One exception, not particularly relevant to soil, is the possibility that the hazards from estimated releases of fossil fuel carbon dioxide to the atmosphere by the end of this century might make nuclear central station power appear much more attractive (NAS-NRC, 1966b).

A unique, nonscientific aspect of the present problem of environmental radioactive contamination is that the man-caused releases of these materials into the environment have occurred, preponderantly, as a result of-not in spite of-specific decisions by nations as a whole. (There have been a few accidents, of course, but they have had mostly local consequences.) The question, up to now, has not been that faced by, for example, those concerned about the pros and cons of organic pesticides, where there is a clearer-cut issue of economic and health gains and losses. Though we speak somewhat out of our field, the problem there seems to us to be more clearly a question of preventing misuse and abuse. A recent symposium (NAS-NRC, 1966b) on scientific aspects of pest control reinforces this view. For radioactive materials, however, much of the past public debate seems to have been based on the tacit assumption that there is no legitimate use whatever associated with a release of such materials to the environment; this assumption seems to us to be related to other issues in addition to that of quality of the environment.

In succeeding sections of this paper we shall discuss, first, the kinds and present abundances of radionuclides in soils; second, soil and plant relationships of those radionuclides; and, finally, the significance of present levels in soil.

ABUNDANCE IN SOIL OF NATURAL AND MAN-MADE RADIONUCLIDES

All soils contain alpha, beta, and gamma radiation emitters, and hence all are radioactive to some extent. The great majority of these radioactive substances occur naturally and hence cannot be regarded as contaminants in the usual sense of the word. The man-made fission products do, of course, constitute a new factor in man's environment.

Naturally Occurring Radioisotopes

The most abundant radioactive substance found in the soil is potassium. The activity is due to potassium 40, one of the several naturally occurring isotopes of potassium. It occurs in average soil to the extent of about 20,000 millicuries per square mile to a depth of 1 foot (Alexander et al., 1960). All potassium-bearing fertilizers, of course, add radioactivity to the soil. Since potassium is taken up in large amounts by high-grade forages such as alfalfa and clovers, potassium 40 is the principal source of internal irradiation of grazing animals that originates in the soil.

On the basis of radioactivity, the related radioactive isotope rubidium 87 is present in soils to the extent of one or two orders of magnitude less than potassium. It is of less concern than potassium. It emits a beta ray of about one-fourth the energy of that of potassium 40.

Three rare earth elements, lanthanum, samarium, and lutetium, also the element rhenium, occur in trace amounts in soil, and have radioactive isotopes. Together, these four may contribute about 15 millicuries of radioactivity per square mile to the total. Since these elements are taken up very slightly by plants, they contribute little to the dosages to biological systems.

The remaining group of naturally occurring radioactive substances found in the soil are uranium and thorium and their decay chain products (Alexander et al., 1960). The total radioactivity of this group usually ranges from that of potassium to one order of magnitude less. The radionuclides of particular significance to the radioactive body burden of humans are radium 226 and radium 228, because of their similarity to calcium, and several daughter products of radium 226, namely radon 222, lead 210, and polonium 210 (United Nations, 1966).

As was pointed out in the Tukey Report, phosphatic fertilizers may contain uranium and its decay products in small amounts. Plants, such as tobacco, that contain large amounts of minerals elements, may have increased radioactivity as a result of uptake from the fertilizer used to produce the crop (Tso et al., 1964). The significance, if any, of the quantities of radium 226, lead 210, and polonium 210 involved has not yet been established.

Fission Products in Soil

When fresh fission products are released to the atmosphere, as in weapons testing or use, a great many radioactive elements are deposited on the soil. Most of them have short half-lives and are reduced to negligible amounts within a few years. Because of the limited test ban treaty of 1963, it has now been four years since substantial amounts of fresh fission products have been released into the air. Hence most of the short-lived products are no longer found in appreciable quantities.

Of those that remain, strontium 90, which has a half-life of about 28 years, is the second most abundant. It is the one about which most concern is usually felt, and perhaps rightly so, since its similarity to calcium brings it into the food chains and deposits it along with calcium in the bones of man and animals, where some of it remains for years. We recognize that strontium 90, like any radionuclide, in some quantities would be detrimental to human health. However, the soil levels found at the present time-the average value for the United States is about 150 millicuries per square mile-are not the major source of man's exposure to radiation.

Cesium 137 is now the most abundant fission product in the environment. It is produced in amounts of 1.6 times as much as strontium 90, has about the same half-life, 30 years, and is found in most soils in about the same ratio to strontium 90 as when produced. It is generally more tenaciously held by the soil than strontium 90 and hence has a somewhat different redistribution and plant availability from strontium 90. Since cesium is similar in its chemical properties to potassium, it is metabolized in the bodies of grazing animals and enters man's diet both in milk and in meat. Its average residence time in the human body is variable, but even in adults relatively short, of the order of a few months (United Nations, 1966). At present the cesium 137 levels in soils are adequately estimated by multiplying the strontium 90 values by a factor of 1.6. Thus, if the average value for strontium 90 in the United States now is 150 millicuries per square mile, the cesium 137 level is about 240.

The strontium 90-yttrium 90 and cesium 137-barium 137 parent-daughter pairs account for most of the biologically available man-made nuclides found in the soil at the present time. The other man-made nuclides present in soils in the greatest abundance include cerium 144-praseodymium 144, ruthenium 106-rhodium 106, promethium 147, and antimony 125; the nuclides of this group are only very slightly available to plants and hence even when present in soil do not get into foods and feed in significant amounts.

Thus we come to the conclusion that the detailed discussion of man-made radionuclides derived from soil which occur in man's current food supply can be restricted to two fission products, strontium 90 and cesium 137. There is also, however, a contribution of the man-made nuclides in soil to the external radiation exposure dose of people and animals.

Carbon 14 in Soils

Carbon 14, which has a radioactive half-life of 5730 years, occurs both naturally and as a result of nuclear testing from the capture of neutrons by nuclei of nitrogen 14 (Glasstone, 1962). The incorporation of atmospheric carbon 14 into soil organic matter is extremely slow, with a half-time of hundreds of years. The carbon 14 content of food plants will not be appreciably affected by increases in the carbon 14 content of the organic matter, because the plants derive the bulk of their carbon directly from the atmosphere (NAS-NRC, 1966a).

SOIL BEHAVIOR AND SOIL-PLANT RELATIONSHIPS OF RADIONUCLIDES

Strontium 90

Part of the strontium 90 that reaches agricultural land from the atmosphere is deposited directly on vegetation and root mats rather than on the soil itself. The contamination of vegetation by this pathway has been a major source of the strontium 90 in the human diet in recent years, but since it is discussed elsewhere in this volume it will not be considered here.

Most of the strontium 90 reaching the soil from the stratosphere has been in a soluble form (Bryant et al., 1960). In solution it is subject to rapid adsorption on soil particles by the process of cation exchange. The adsorbing constituents are clay minerals and organic matter. While in this exchangeable state, radiostrontium has approximately the same mobility as that of exchangeable stable strontium and calcium.

While it is located at the surface of bare soils, strontium 90 is subject to redistribution by runoff and by erosion along with the particles to which it is attached. The result can be a significantly increased concentration of strontium 90 in lower-lying areas where the eroded soil material accumulates (Menzel, 1960).

The downward movement in soil of strontium 90 due to such factors as percolating rain water, diffusion, and animal burrowings is relatively slow. Even in the recent sampling for strontium 90 content of undisturbed grass-covered soils, collection of samples to a depth of only 8 inches has been adequate for obtaining virtually all the strontium 90 in the profile (Alexander et al., 1961). The distribution in cultivated soil, however, is quite different. Depending on the type and extent of tillage practices, cultivation tends to distribute the strontium 90 uniformly through the cultivated layer, or to place it mainly at the bottom of the cultivated layer, where it is subject to further downward movement. The uptake by root systems of various types is affected to some extent by the distribution pattern. The presence of salts in irrigation water (Miller and Reitemeier, 1963) and the fertilization and amendment of soils (Squire, 1966) generally increase the rate of downward movement.

Soluble and exchangeable strontium 90 can be regarded as available sources for plants. There is evidence, however, from chemical extractions and from agronomic field experiments (Squire, 1966) that, at least in some soils, a part of the strontium 90 content becomes fixed in a nonexchangeable form, which has been shown to be unavailable to plants (Roberts and Menzel, 1961). Since fixation, when it is observed in the field, usually appears to involve less than 10% of the total strontium 90, and its duration has not been established, it is not considered in the long-term assessment of strontium 90.

In order to make generalized comparisons of the relative availabilities of various radioactive elements to plants, Menzel (1965) examined the results of a number of field and greenhouse experiments from which the relative concentration factor of an element in the plant and in the soil could be ascertained, that is, parts per million in dry plant material over parts per million in dry soil. On this basis, the elements were divided into five groups, namely (a) strongly concentrated, (b) slightly concentrated, (c) not concentrated, (d) slightly excluded, and (e) strongly excluded. Strontium is classified in the second group, slightly concentrated, together with the similar elements calcium and magnesium. An increase in the available calcium supply of a soil often reduces the radiostrontium content, or the ratio of radiostrontium to calcium, of plants. Despite a general lack of discrimination between strontium and calcium with respect to total uptake by the aboveground portion of the plant, specific plant parts do exhibit differences in strontium content and in the ratio of strontium to calcium. Roots generally show higher values of the ratio than leaves, but fruits and grains show lower values.

A single crop generally will remove from 0.1 to 1% of the soil content of strontium 90. The actual amount of uptake depends on a large number of factors, including the kind and size of the crop; the soil type; application of lime, fertilizers, or other amendment; and cultivation practices (Menzel, 1963).

Cesium 137

The cesium 137 content of foods and feeds, especially in north temperate zone areas, has been derived preponderantly from direct atmospheric deposition on vegetation, and uptake from root mats and the organic layers of permanent pastures (United Nations, 1966). Another reason for this is the intensive fixation of cesium 137 in mineral soil horizons in a nonexchangeable form by the clay mineral vermiculite and vermiculitic interlayers of interstratified micaceous minerals (Sawhney, 1966). The relative absorption of radiocesium from tropical soils which do not contain such minerals is much greater (United Nations, 1966).

This widespread fixation results in both a very low mobility in mineral soils and a low uptake from them by plants. On the other hand, the mobility of cesium within the plant is relatively high, in contrast to that of strontium, which moves primarily away from the base. When the available potassium level of a soil is low, applications of potassium fertilizer may decrease the uptake of cesium 137 (Nishita et al., 1961). It has been observed, however, that the uptake by lowland rice growing in paddy soil is increased by application of nitrogen in the ammonium form (Tensho et al., 1961).

Menzel's classification of elements on the basis of relative concentration factors places cesium 137 in the category of "slightly excluded." (Ruthenium is also in this category.) The uptake from soil by a single crop is usually less than 0.1% of the soil's content.

Where the interest is in external gamma radiation rather than food chain contamination, however, it whould be noted that the contribution of the cesium 137-barium 137 pair is directly proportional to its total accumulation on the ground (United Nations, 1966).

Rare-Earth-like Nuclides

The elements cerium, promethium, and yttrium have been placed by Menzel in the category of "stongly excluded." (Antimony is also placed here.)

There is evidence that when the soil pH exceeds 7 the rare-earth-like elements cerium and yttrium are strongly bound by clay minerals, organic matter, and aluminum and iron sesquioxides. When the pH is below 7, however, only the organic matter and sesquioxides appear to bind them tightly.

SIGNIFICANCE OF PRESENT LEVELS OF RADIONUCLIDES IN SOILS

As was mentioned earlier, one way of showing the significance of levels of man-made radionuclides in the environment is to compare the estimated radiation risk associated with them to that associated with natural radiation. The United Nations Scientific Committee on the Effects of Atomic Radiation has been making such comparisons periodically, and recently reported such a comparison for the 12-year period 1954 through 1965 (United Nations, 1966). Three categories of comparative risk for the general world population are expressed "in terms of the periods of time during which natural radiation would have to be doubled to give a dose increase equal to the total doses expected by the year 2000 from the current contamination of the environment due to past nuclear weapons tests." The doses and estimated periods given by the Committee are approximately as follows: (a) gonad dose, related to hereditary effects, 0.75 year, of which 0.4 year is ascribed to cesium 137; (b) bone marrow dose, related to leukemia induction, 1.5 years, of which 1.25 years are ascribed to cesium 137 and strontium 90; and (c) dose to cells lining bone surfaces, related to bone tumor induction, 2.5 years, of which 2 years are ascribed to cesium 137 and strontium 90. The estimated dose rates from natural sources and dose commitments due to nuclear explosions from which these periods were calculated are tabulated in the Appendix.

The variability observed in the past of relationships between the levels of radionuclides in soils and those in the human diet is one of the reasons for the lack of radioactivity standards for agricultural soils. The Federal Radiation Council has stated that four radionuclides are particularly important in the consideration of the radioactive contamination of food, namely, iodine 131,[1] strontium 89, strontium 90, and cesium 137. In May 1965, the President approved, for the guidance of federal agencies, recommendations submitted by the Council concerning the last three nuclides present as worldwide contamination from stratospheric fallout from past atmospheric nuclear testing (Federal Register, 1965).

One of those recommendations was that "nationwide programs to reduce potential exposure of the population from gradually increasing levels of environmental contamination, such as that associated with worldwide fallout, are not necessary now nor for future levels of fallout from past testing." This recommendation was a consequence of the Council's conclusion that "the health risk from radioactivity in food over the next several years would be too small to justify protective actions to limit the intake of radionuclides either by diet modifications or by altering the normal distribution and use of foods, particularly milk and dairy products" (Federal Radiation Council, 1965).

It is of interest here that the general levels of the longer-lived man-made radionuclides in foods in the United States reached their peak in 1964, before the publication of the recommendation. Only a part of the strontium 90 and cesium 137 that has entered the national diet and thereby contributed to the radiation dose of the population originated from soil accumulations. The currently decreased rates of deposition of the two nuclides and the further radioactive decay of the existing quantities in the soil mean that their concentrations in the diet are at present expected to continue to decrease.

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[1] Iodine 131, which has a half-life of 8 days, exists for too short a time to be considered with respect to soil contamination.

APPENDIX

These two tables essentially duplicate Tables I and II on pages 5 and 6 of a United Nations (1966) report. The footnotes of the two tables and the pertinent sections of the text of that report should be examined for a thorough explanation of the terms and the values.

Table 1. Dose rates due to external and internal irradiation from natural sources in "normal" areas

Source of irradiation	Dose rates, mrad/y		
	Gonads	Cells lining bone surfaces	Bone marrow
External irradiation			
Cosmic rays			
Ionizing component	28	28	28
Neutrons	0.7	0.7	0.7
Terrestial radiation, including air	50	50	50
Internal irradiation			
K^{40}	20	15	15
Rb^{87}	0.3	<0.3	<0.3
C^{14}	0.7	1.6	1.6
Ra^{226}	. . .	0.6	0.03
Ra^{228}	. . .	0.7	0.03
Po^{210}	0.3	2.1	0.3
Rn^{222}, dissolved in tissues	0.3	0.3	0.3
Total	100	99	96
Percentages from alpha particles and neutrons	1.3	4.4	1.4

Table 2. Dose commitments from nuclear explosions

Tissue	Source of radiation	Dose commitments, mrad, for period of testing 1954-1965
Gonads	External	
	Short-lived	23
	Cs^{137}	25
	Internal	
	Cs^{137}	15
	C^{14}	13
	Total	76
Cells lining bone surfaces	External	
	Short-lived	23
	Cs^{137}	25
	Internal	
	Sr^{90}	156
	Cs^{137}	15
	C^{14}	20
	Sr^{89}	0.3
	Total	240
Bone marrow	External	
	Short-lived	23
	Cs^{137}	25
	Internal	
	Sr^{90}	78
	Cs^{137}	15
	C^{14}	13
	Sr^{89}	0.15
	Total	150

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SYSTEMS ANALYSIS OF ^{134}CESIUM KINETICS IN TERRESTRIAL MICROCOSMS[1]

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Abstract. Laboratory experiments were conducted to determine patterns and rates of ^{134}Cs exchange in microecosystems composed of different combinations of radioactive leaf litter, soil, microflora, millipedes, and aqueous leachate. Rate constants were determined by fitting models to data with an analog computer. Simulations with the models permitted comparisons of different microcosms in terms of time to radiocesium equilibrium, steady state concentrations, concentration factors, input and output fluxes, turnover rates, and stability.

Rate constants varied with different compartment combinations, indicating both qualitative and quantitative differences in the cesium exchange patterns within different systems. This result is generalized: transfers of energy and matter in ecosystems are functions of networks which define intercompartmental interactions; internal coupling should be considered a significant variable in investigations of ecosystem processes.

Points of particular interest derived from the computer simulations are (i) organism concentration factors for a material may vary in different systems, depending upon how the organism is coupled to other compartments; (ii) total flux of a material in a steady state system may vary considerably from that in another system which receives identical input; (iii) material turnover within compartments and in the system as a whole tends to increase as more compartments are added; and (iv) stability of material concentration does not appear to increase with system complexity.

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INTRODUCTION

Investigations of mineral cycling in terrestrial ecosystems are hindered by difficulties of separating soil organisms, plant roots, dead organic matter, and the mineral soil. Consequently, most studies consider only two compartments, such as soil-litter or soil-plant, and usually only at some experimental endpoint (harvest). Investigations of mineral flows between multiple compartments have been few (Jansson 1958, Remezov 1959, Witherspoon 1964, Witkamp and Frank 1964, Neel and Olson 1962, Olson 1965), and only the last two of these have given explicit attention to exchange kinetics. Whittaker (1961) has attempted to determine the kinetics of ^{32}P in aquatic microcosms. The present study employs two innovations to develop fuller understanding of mineral cycling in a series of experimental micro-ecosystems, one involving laboratory syntheses of progressively more complex systems, and the other involving use of an analog computer to determine the kinetics of intercompartmental transfers.

Microcosms of increasing complexity were synthesized by adding one compartment at a time. Five compartments were used: ^{134}Cs-labeled oak leaves, mineral soil, microflora, millipedes and an aqueous leachate. Radioactivity in each compartment was determined as a function of time, with ^{134}Cs in the microflora computed as the difference between activity leached from sterile- and non-sterile leaves. This stepwise approach to construction of multicompartmental systems permits evaluation of the effects of each added compartment on the mineral's dynamics.

Empirical data take the form of curves of radiocesium activity in each compartment graphed against time. Such information by itself does not specify transfer pathways, rates and fluxes along these pathways, or transfer mechanisms. It is possible, however, to determine these system characteristics by adjusting an analog computer model to fit the experimental data. This procedure results in a description of radiocesium kinetics for each microcosm in terms of a system of differential equations. The equations specify and quantify transfer pathways, and permit additional information to be developed by computer simulations of experiments which would be difficult or impossible to perform in the laboratory.

Miss Bonnie McGurn assisted in conducting the laboratory experiments, and Drs. D. A. Crossley and D. E. Reichle provided helpful criticism and discussion.

MATERIALS AND METHODS

Experimental

Microcosms were established in 60 ml glass funnels, inside diameter 4 cm, with fritted, medium porosity filters. The funnels were seated on 125 ml suction flasks each containing a counting tube for collection of leachate. Triplicates of the following systems were established: (i) sterile white oak (*Quercus alba* L.) leaves, (ii) leaves and microflora, (iii) leaves, microflora and millipedes, and (iv–vi) same as i–iii but placed on the surface of a 1 cm layer of silt-loam (pH 6.4, 12.6% organic matter, 27% moisture). The microcosms were maintained under identical conditions at room temperature (about 25°C).

The radioactive leaves were collected in July 1961 from small trees trunk-labeled (Witherspoon 1964) with ^{134}Cs a year before. Each funnel received 1 g of air-dried leaf material cut slightly smaller than 4 cm diameter. Leaves and soil were sterilized with 12% ethylene oxide (16 hr, 8 psi, 40°C) after which microflora and millipedes were added. Five millipedes (*Dixidesmus erasus* Loomis), averaging 392 mg total fresh weight and newly-collected from neighboring forests, were added to each funnel requiring millipedes. Dead millipedes were replaced daily if necessary and assayed for ^{134}Cs activity. Microflora was introduced in 1 ml of supernatant from 10 g wet weight of oak leaves shaken for 15 min with 100 ml of sterile water. This inoculum was administered to funnels requiring microflora as part of the first leaching at the start of the experiments. For each leaching, 8 ml of sterile water was dripped from a pipette as uniformly as possible over the contents of each funnel. This procedure was repeated every 2–3 days to approximate mean precipitation in Oak Ridge (2.5 cm/wk). During leaching, 10 cm Hg vacuum was applied. Leachate volumes were recorded and radiocesium activity of 5 ml aliquots was determined by NaI(Tl) scintillation counting. Between leachings, positive pressure of about 1 cm Hg was maintained in the flasks to prolong millipede survival by providing aeration. After 18 days and 9 leachings, the experiments were terminated and ^{134}Cs activity of remaining litter, soil and millipedes measured.

Computational

A block diagram of the litter-soil-microflora-millipede-leachate microecosystem, indicating all possible transfer routes, is shown in Figure 1. This system is reducible to fewer compartments by letting ^{134}Cs transfers be zero along appropriate pathways. All the microcosms thus implied in Figure 1 can be regarded as closed with respect

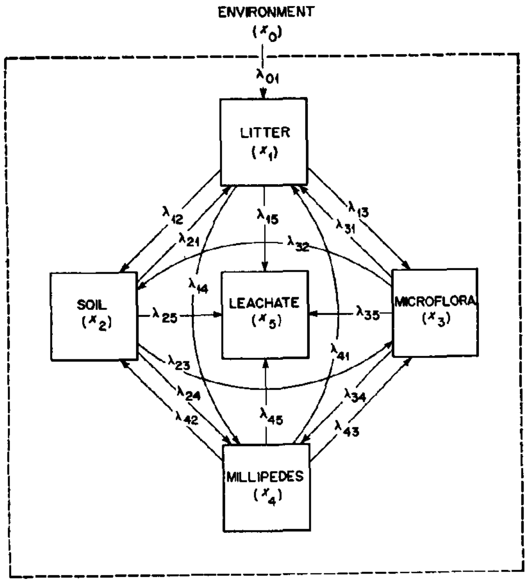

FIG. 1. Block diagram of litter-soil-microflora-millipede-leachate microecosystem showing all possible routes of cesium transfer and associated rate constants, λ_{ij} ($i = 0,1,\ldots,4$; $j = 1,2,\ldots,5$).

to the radioisotope, even though radioactivity was removed in successive leachings, by considering the cumulative leachate as a sink (no back transfers to other compartments) within the system of definition. Thus, the only loss of activity for computational purposes is by radioactive decay, and this is negligible in an 18-day experiment (^{134}Cs half-life $= 2.07\,y$).

Let X (a constant) be the initial radioactivity introduced in oak litter, and hence the total activity of the microcosm throughout an experiment. This activity will move from one compartment to another with time. If $X_j(t)$ is the total amount of radioactivity in compartment j at time t, then, since no activity is lost in an experiment, $\Sigma_j X_j = X =$ constant. If the mass of compartment j at time t is $m_j(t)$, then the concentration or activity-density of radiocesium in the compartment at time t is $x_j = X_j/m_j$. Letting $\lambda_{ij}(t)$ be a function expressing the rate of ^{134}Cs transfer from compartment i to compartment j, the rate of change of radioisotope concentration in the j'th compartment is the balance between incomes and losses:

$$\dot{x}_j = \sum_i \lambda_{ij} x_i - \sum_i \lambda_{ji} x_j , \qquad (1)$$

$$(i,j = 1,2,\ldots,5;\ i \neq j;\ 0 \leq \lambda_{ij}, \lambda_{ji} < \infty;\ 0 \leq x_i, x_j \leq 1)$$

where $\dot{x}_j$ is the first derivative of x_j with respect to time. Since the experimental systems were all non-stationary (at least one $\dot{x}_j \neq 0$ during the period of observation) and since a transient solution of a differential equation corresponds to a unique transient behavior, equations (1) can be made to describe uniquely ^{134}Cs exchanges in the microcosms by finding appropriate functions, $\lambda_{ij}(t)$. To do this a simplest possible model was programmed for study on an Electronic Associates TR–10 analog computer. This proved adequate for description of the experimental results, and further refinements were unnecessary.

The model assumed first order kinetics: that transfer of ^{134}Cs from compartment i to compartment j is directly proportional to the radioisotope concentration in compartment i. With this assumption, the λ_{ij} in equations (1) become rate *constants*, having units $\{t^{-1}\}$.

To normalize the system equations so that different microcosms with different values of X could be compared, the fraction of radioactivity in each compartment relative to total system activity, $y_j = x_j/X$, was used as a variable for work on the computer. This has no effect on the rate constants to be determined, as the normalized system equations show:

$$\dot{y}_j = \frac{\dot{x}_j}{X} = \sum_i \lambda_{ij} \frac{x_i}{X} - \sum_i \lambda_{ji} \frac{x_j}{X} = \sum_i \lambda_{ij} y_i - \sum_i \lambda_{ji} y_j . \qquad (2)$$

$$(0 \leq y_i, y_j \leq 1)$$

The computing procedure was to fit program-generated curves of $y_j(t)$ to empirical curves by adjusting potentiometers representing the λ_{ij} and λ_{ji}, thereby obtaining numerical values for these parameters and simultaneous solutions of the system equations (1 and 2) for each experimental microcosm.

RESULTS

The five compartments can be labeled as follows: i, $j = 1 \equiv$ oak litter, $2 \equiv$ soil, $3 \equiv$ microflora, $4 \equiv$ millipedes and $5 \equiv$ leachate (Fig. 1). The environment is compartment 0. Possible combinations of litter-leachate and other compartments are 1–5, 1–2–5, 1–3–5, 1–4–5, 1–2–3–5, 1–2–4–5, 1–3–4–5, and 1–2–3–4–5. Of these, 1–4–5 and 1–2–4–5 are not experimentally feasible because of difficulties of sterilizing millipedes. The remaining combinations, labeled I-VI, respectively, were investigated in six experiments whose results are summarized in Figure 2 and Table 1.

Combination I (litter-leachate).—As shown in Figure 2a, ^{134}Cs was transferred from litter to leachate at a rate of $\lambda_{15} = 0.037$ day^{-1}, 3.7% per

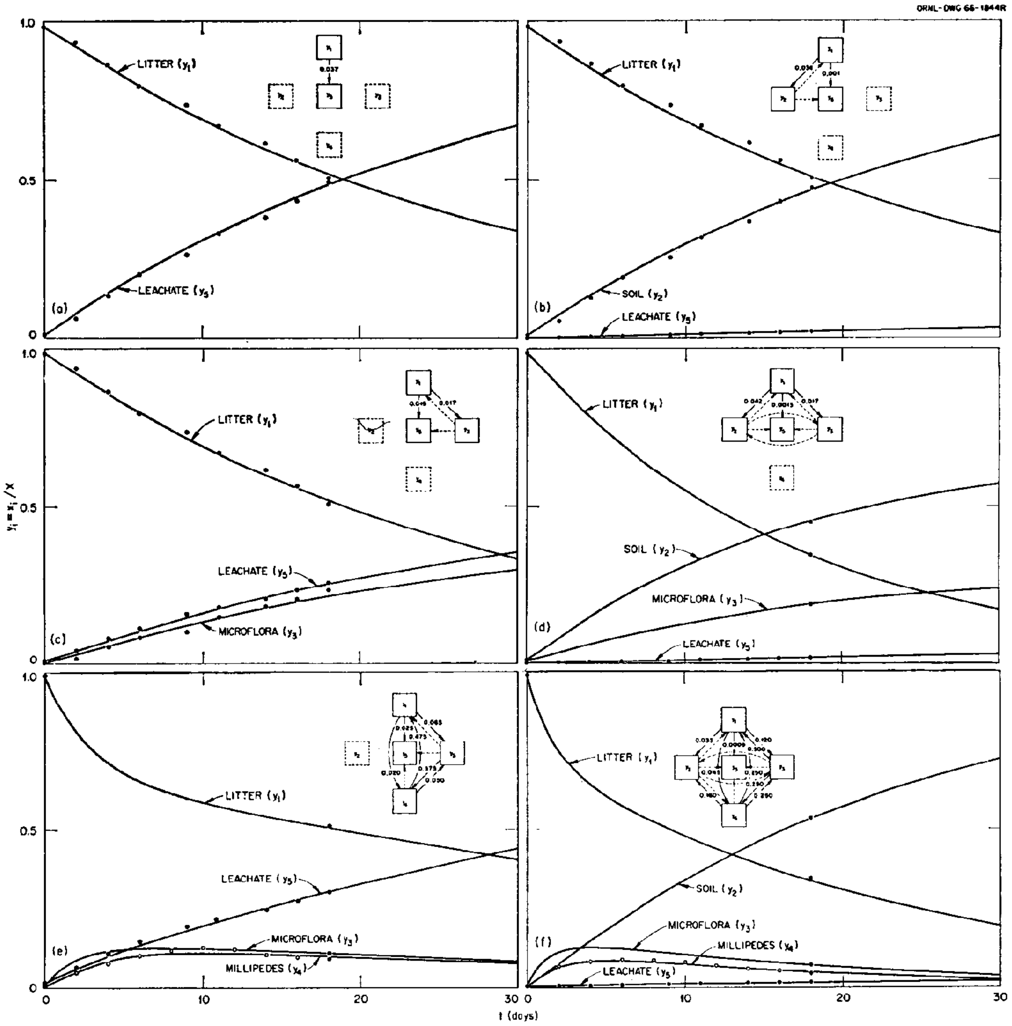

FIG. 2. Analog computer curves of changes in relative distribution (y_j) of radiocesium in the microcosms of Combs. I–VI (Figs. a–f, respectively). Means of three replicates are shown as solid circles. Open circles represent estimates of relative cesium concentration in millipedes based on radioassays of animals which died. Insets show compartment combinations and rate constants (day^{-1}) for each indicated transfer route. Pathways over which no cesium was transferred are illustrated by broken arrows.

day. System equations will not be written explicitly hereafter, but for the purpose of illustrating how the microcosm behaviors depicted in Figure 2 are described by the model (equations 1 and 2), the system equations for the present experiment are

$$\begin{cases}\dot{x}_1 = -0.037\,x_1\\ \dot{x}_5 = 0.037\,x_1\end{cases} \quad\text{or}\quad \begin{cases}\dot{y}_1 = -0.037\,y_1\\ \dot{y}_5 = 0.037\,y_1\end{cases}$$

Combination II (litter-soil-leachate).—Addition of soil sharply reduced transfer of radiocesium from litter to leachate (Fig. 2b). The total loss rate from litter was the same as in Combination I ($\lambda_{12} + \lambda_{15} = 0.037\ \text{day}^{-1}$, Table 1), but now 0.036 day^{-1} went to soil and only 0.001 day-1 to the leachate. Once in the soil radiocesium was held tightly, as indicated by non-leachability ($\lambda_{25} = 0$) and absence of back transfer to litter ($\lambda_{21} = 0$).

Combination III (litter-microflora-leachate).—Loss of ^{134}Cs from litter was essentially the same as in Combination I, 0.036 day^{-1} (Table 1). Of the total litter loss, 0.017 day^{-1} was transferred to microflora and 0.019 day^{-1} to the leachate (Fig. 2c, Table 1). In agreement with *in vitro* leaching experiments with microflora, radiocesium in

TABLE 1. Rate constants, day^{-1}

	Combinations					
Parameters	I (1-5)	II (1-2-5)	III (1-3-5)	IV (1-2-3-5)	V (1-3-4-5)	VI (1-2-3-4-5)
λ_{12}	—	0.036	—	0.042	—	0.033
λ_{13}	—	—	0.017	0.017	0.065	0.120
λ_{14}	—	—	—	—	0.020	0.045
λ_{15}	0.037	0.001	0.019	0.0013	0.025	0.0009
$\sum_j \lambda_{1j}$	0.037	0.037	0.036	0.060	0.110	0.199
λ_{21}	—	0	—	0	—	0
λ_{23}	—	—	—	0	—	0
λ_{24}	—	—	—	—	—	0
λ_{25}	—	0	—	0	—	0
$\sum_j \lambda_{2j}$	—	0	—	0	—	0
λ_{31}	—	—	0	0	0	0.500
λ_{32}	—	—	—	0	—	0
λ_{34}	—	—	—	—	0.375	0.250
λ_{35}	—	—	0	0	0	0
$\sum_j \lambda_{3j}$	—	—	0	0	0.375	0.750
λ_{41}	—	—	—	—	0.475	0.250
λ_{42}	—	—	—	—	—	0.160
λ_{43}	—	—	—	—	0.050	0.250
λ_{45}	—	—	—	—	0	0
$\sum_j \lambda_{4j}$	—	—	—	—	0.525	0.660

the microflora was non-leachable ($\lambda_{35} = 0$). No reverse transfer from microflora to litter was indicated ($\lambda_{31} = 0$). The rate of leachate gain was reduced compared to when microflora were absent (Comb. III vs. I), but not as much as when soil was present (Comb. III vs. II).

Combination IV (litter-soil-microflora-leachate)—Soil and microflora together had a synergistic effect which markedly increased the rate of cesium loss from litter ($\lambda_{12} + \lambda_{13} + \lambda_{15} = 0.060$ day^{-1}, Table 1). As shown in Figure 2d and Table 1, transfer from litter to soil was increased to $\lambda_{12} = 0.042$ day^{-1} compared to 0.036 in Combination II. Accumulation by the microflora, however, was unaffected by soil ($\lambda_{13} = 0.017$ as in Comb. III). Leachability of the litter ($\lambda_{15} = 0.0013$) was essentially as in Combination II. Hence, the synergism appears to be an effect mainly on the ability of soil to acquire cesium from the litter, which is difficult to understand in view of previous results indicating that microflora do not alter the rate of loss from the litter (Comb. III vs. I). Furthermore, no direct exchanges between soil and microflora are indicated ($\lambda_{23} = \lambda_{32} = 0$), and consequently the character of the microflora effect on litter-soil exchange is not apparent. As in Combinations II and III, soil and microflora radioactivity was non-leachable ($\lambda_{25} = \lambda_{35} = 0$), and also there was no cesium feedback from these compartments to the litter ($\lambda_{21} = \lambda_{31} = 0$).

Combination V (litter-microflora-millipedes-leachate).—The open circles in Figure 2e represent estimates of y_4 for total millipedes based on radioassays of animals which died and were removed. The fit of the model to these data is not too satisfactory: the millipede curve does not rise high enough between 6 to 14 days and does not fall rapidly enough toward the end of the observation period. Whether this difficulty is primarily with the model or with the extrapolated data is uncertain, but the fact that a better fit was obtained in the next, more complex combination which included soil (Fig. 2f) is good reason for confidence in the model.

The Combination V results (Fig. 2e, Table 1) indicate that when both microflora and millipedes are present the total rate of cesium loss from litter ($\lambda_{13} + \lambda_{14} + \lambda_{15} = 0.110$, Table 1) was tripled compared to Combinations I–III and almost doubled compared to Combination IV. The rate of transfer from litter to microflora was four times greater than in Combination III ($\lambda_{13} = 0.065$ vs. 0.017), presumably due to action of millipedes upon the litter. This action is also reflected in increased leachability of litter cesium ($\lambda_{15} = 0.025$ vs. 0.019 in Comb. III).

Despite these indications of millipede effects on litter, the rate of radiocesium transfer from litter to millipedes was fairly low, $\lambda_{15} = 0.020$ day^{-1}. In contrast, uptake rate from the microflora was about 19 times greater ($\lambda_{34} = 0.375$). Based on these results, and prompted by laboratory observations of no visible fungal mycelia in microcosms containing *Dixidesmus* but abundant growths otherwise, it was originally thought that the model denoted a 19-fold perference of *Dixidesmus* for microflora over litter. This is not necessarily true, as illustrated by the following examples of two-compartment exchanges.

Let compartment i have biomass m_i and cesium concentration x_i, compartment j have biomass m_j and concentration x_j, and suppose $x_i > x_j$. (i) If biomass is transferred from i to j ($\lambda_{ij} > \lambda_{ji} = 0$), then compartment i loses mass but its cesium concentration does not change (homogeneous distribution of the mineral within the mass is assumed for purposes of the argument). Compartment j gains biomass which is of higher radioisotope concentration than that within the compartment, and therefore x_j increases. As the process continues, both activity-densities approach equality, $x_j \rightarrow x_i$. (ii) If biomass is transferred from j to i ($0 = \lambda_{ij} < \lambda_{ji}$), compartment i gains biomass with cesium concentration x_j, and therefore x_i decreases. Compartment j loses mass but its concentration of radiocesium is unchanged. Continued exchange leads in the direction $x_i \rightarrow x_j$. (iii) If both forward and reverse exchanges occur simultaneously ($\lambda_{ij}, \lambda_{ji} > 0$), the cesium concentrations will move toward an equilibrium defined by $x_{j(eq)} = \frac{\lambda_{ij}}{\lambda_{ji}} x_{i(eq)}$. The second example, where compartment i gains biomass and consequently has its cesium concentration reduced, illustrates why biomass and tracer transfers cannot both be represented by the same rate constants. A 19-fold difference in rates of cesium input from two compartments cannot be interpreted as a 19-fold food preference.

As with the microflora in this and preceding combinations, millipede radioactivity was nonleachable ($\lambda_{35} = \lambda_{45} = 0$). However, unlike the microflora which did not transfer ^{134}Cs back to the litter ($\lambda_{31} = 0$), the millipedes did so at a high rate ($\lambda_{41} = 0.475$). In addition, the animals also transferred radiocesium to the microflora at a rate of $\lambda_{43} = 0.050$ day^{-1}.

Combination VI (litter-soil-microflora-millipedes-leachate).—Results with this most advanced microcosm are given in Figure 2f and Table 1. Numerous points of comparison with previous combinations are possible, and the most systematic way to proceed is down the last column of Table 1.

The rate of cesium transfer from litter to soil ($\lambda_{12} = 0.033$) was less than in other combinations in which soil was present. In Combination IV, compared to II, microflora increased the rate of movement from litter to soil. With millipedes present (Comb. VI), this effect is apparently nullified. One reason is that the rate of movement from litter to microflora was about 7 times greater ($\lambda_{13} = 0.120$ in Comb. VI vs. 0.017 in Comb. IV). Another is that the rate of transfer from litter to millipedes was more than doubled in the presence of soil ($\lambda_{14} = 0.045$ vs. 0.020 in Comb. V). The basis for this soil-millipede interaction is not apparent except, perhaps, that the normal habitat of these animals was better approximated here than in Combination V, resulting in more normal rates of food consumption. Leachability of litter cesium, $\lambda_{15} = 0.0009$ day^{-1}, was low as in Combinations II and IV, which also had soil present. That microflora and millipedes substantially increased the mobility of litter cesium is clear from the total litter loss rate ($\lambda_{12} + \lambda_{13} + \lambda_{14} + \lambda_{15} = 0.199$), which is almost 6 times greater than in Combinations I–III, more than 3 times greater than in Combination IV, and almost twice as great as in Combination V.

Soil is clearly a cesium sink at the low concentrations in these experiments, since none of the microcosms studied contained a compartment capable of acquiring the mineral from soil ($\lambda_{2j} = 0$ for all $j \neq 2$; Table 1).

Unlike previous combinations with microflora, radiocesium in this combination was transferred at a high rate from microflora to the litter ($\lambda_{31} = 0.500$). This may be due to millipede feeding since Combination V indicated that these animals obtain cesium from the microflora ($\lambda_{34} = 0.375$ in Comb. V vs. zero in Combs. III and IV without millipedes). The transfer to litter rather than soil ($\lambda_{32} = 0$) verifies the experimentally observable fact that mycelia and other microbial components are associated with litter more than soil. Lack of transfer from microflora to litter in Combination V is unexplained.

The transfer rate from microflora to millipedes, while still high ($\lambda_{34} = 0.250$), is nevertheless reduced compared to Combination V. Soil, the only variable between these two combinations, must be responsible. A physiological difference between microflora in this combination and Combination V is indicated by doubling of the radiocesium loss rate in the presence of soil ($\lambda_{31} + \lambda_{32} + \lambda_{34} + \lambda_{35} = 0.750$ day^{-1}). Nothing is known of the microflora species composition, but it must have been different from Combination V, and this could account for some difference in transfer to millipedes.

Cesium transfer from millipedes to litter was reduced almost half compared to Combination IV ($\lambda_{41} = 0.250$). This is due partly to soil affinity for excreted cesium ($\lambda_{42} = 0.160$), but the combined loss to soil and litter ($\lambda_{41} + \lambda_{42} = 0.410$) is still somewhat less than the lost to litter in Combination V ($\lambda_{41} = 0.475$). The high transfer from millipedes to microflora ($\lambda_{43} = 0.250$ vs. 0.050 in Comb. IV) may be due to improved nutritional and moisture conditions with soil present. This contributed to a higher observed elimination rate for *Dixidesmus* than in Combination V ($\lambda_{41} + \lambda_{42} + \lambda_{43} + \lambda_{45} = 0.660$ vs 0.525), although this difference appears to be due largely to the method of obtaining millipede data: after each leaching, dead millipedes were removed for radioassay and replaced by new animals. Data from the dead specimens were used to represent live animals. No difficulties apparently were encountered through cesium leaching from the dead material ($\lambda_{45} = 0$), but microbial decomposition ($\lambda_{43} = 0.250$) had begun. Assuming no direct transfer to microflora from live millipedes, corrected elimination rates for *Dixidesmus* in Combs. V and VI, respectively, would be 0.475 and 0.410 day^{-1}.[2] These values compare favorably with 0.29 day^{-1} (biological half life = 2.4 days at 20°C), reported for assimilated cesium by Reichle and Crossley (1965), considering the higher temperature of the present experiments and the fact that both assimilated and unassimilated components are taken into account.

In general, the Table 1 results show that, under otherwise similar conditions, rate constants change in microcosms composed of different combinations of the same compartments. From this it can be concluded that patterns of intercompartmental coupling are prime variables to consider in studies of energy and material flows in ecosystems.

DISCUSSION

Pathways of mineral transfer in coupled microecosystems are both identifiable and quantifiable by the procedures employed, namely the simultaneous solution of systems of differential equations with an analog computer. (i) Qualitatively, actual transfer routes of those which are possible were determined. These are illustrated in the insets of Figure 2, the pathways over which no transfers occurred being shown as broken arrows. The numbers of actual routes in the systems of Combinations I–VI were, respectively, 1, 2, 2, 3, 6 and 9. The ratios of actual pathways to possible ones were 1.00, 0.50, 0.50, 0.33, 0.67 and 0.56 (ii) Quantitatively, rates of cesium transfer along the actual routes are given by the values of the parameters, λ_{ij}.

In general, two systems are identical if their parts are the same and the connections between the parts are the same. In Figure 3, systems 1

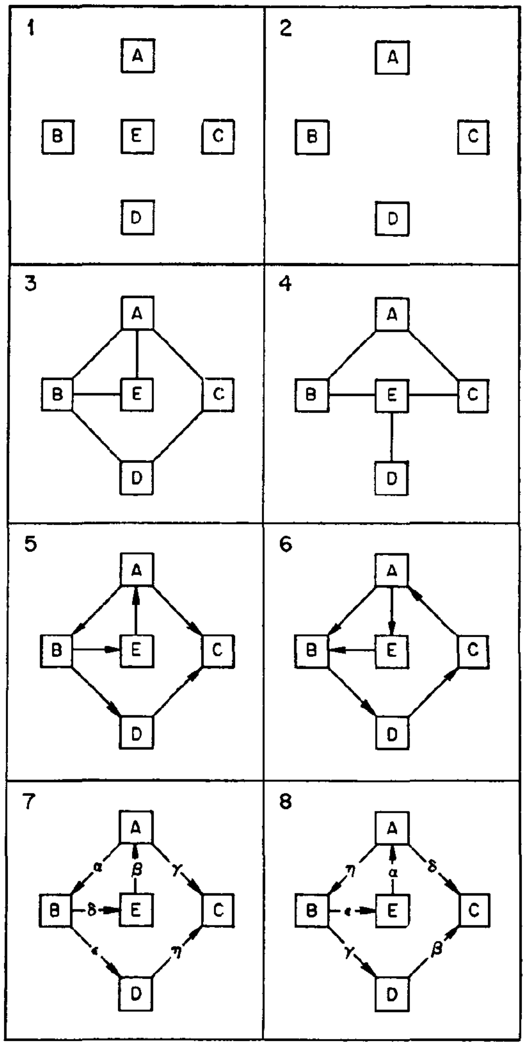

FIG. 3. Examples of non-identical systems (discussion in text).

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[2] The values 0.475 and 0.410 may not be significantly different because of subjectivity in determining best fit in the curve-fitting procedure. Numerical approaches for use with digital computers are now being explored. A preliminary value of λ_{41} is 0.414 day^{-1} (G. M. Van Dyne, personal communication), and that by another 0.470 day^{-1}.

and 2 are different because their components are different; systems 3 and 4 differ because the connections are not the same in the "qualitative" sense given above; in systems 5 and 6 the connections are different in a "relational" or "directional" sense; and systems 7 and 8 differ in the "quantitative" sense that their rate functions are different. None of the systems of Figure 3 are identical, and consequently none will behave precisely the same as another whether it be in reaction to some environmental stimulus, in utilization of energy, or in the cycling of minerals, if these be appropriate system activities. The "structure and function" of these systems is said to be different. Similarly, the six microecosystems of this study have been shown to differ in radiocesium kinetics, with examples (Fig. 2, insets) of each of the reasons for system differences, illustrated in Figure 3, being represented.

Analog Computer Simulations

The microcosm models which have been obtained are operational, and it now becomes possible to study comparative transient and stationary behavior of these systems on the computer, in effect performing experiments which would be difficult or impossible to conduct in the experimental laboratory. The number of experiments possible is infinite, and the ones actually performed were selected to bring out aspects of microecosystem behavior of general ecological interest.

To generate system behavior, a driving or forcing function, $\lambda_{01}\, x_0$, was introduced via the litter compartment (Fig. 1). In the six experiments preceding, there was only an initial cesium concentration in the litter, but no subsequent input from the environment ($\lambda_{01} = 0$). Driving the systems through the litter is somewhat artificial, just as establishing the microcosms with tagged litter is, because in nature each compartment is exposed directly to cesium input as environmental fallout. The experiments might have been more realistic, therefore, if an initial cesium dose had been rained on as part of the first leaching rather than introduced as tagged litter. This would not have changed any system parameters (Table 1), but it would have yielded additional parameters of interest (λ_{0j}; $j = 1, 2, \ldots, 5$). The simulations could then have been driven by multiple inputs. The present model is still very useful for relative comparisons of cesium behavior in the six microcosms. Relationships between radioactivity and voltage, and real time and computer time are clarified in the appendix.

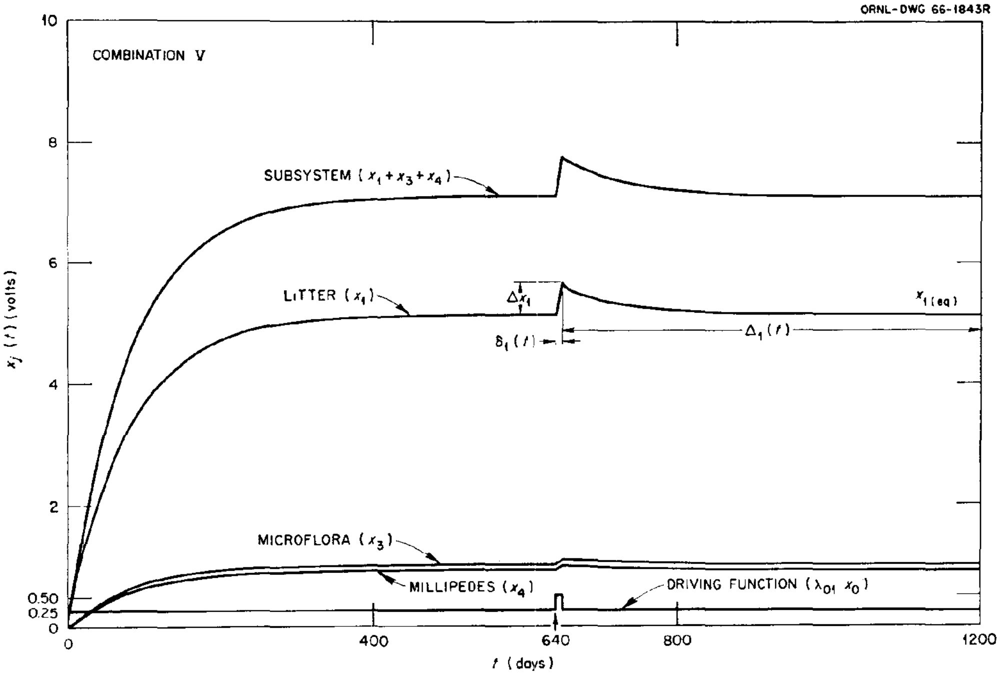

FIG. 4. Computer simulation of time behavior of cesium concentration (x_j) in the Combination V system, with constant input and perturbation after equilibrium. Soil and leachate did not equilibrate and are omitted. Shown is the driving function of 0.25 v, increased to 0.50 v between 640 and 648 days; also litter, microflora and millipede compartments, and the subsystem of these three compartments. The variables $\delta_j(t)$, $\Delta_j(t)$, $x_{j(eq)}$ and Δx_j are illustrated for the litter compartment.

Experiments of 1200 days (3.3 years) duration were run (Fig. 4). The driving function arbitrarily selected was a constant $\beta^{-1}\lambda_{01} x_0 = 0.25$ v sec^{-1}, obtained by letting $x_0 = 10$ v, $\lambda_{01} = 0.0125$ day^{-1}, and β (time-scale factor, see appendix) $= \frac{1}{2}$ sec day^{-1}. All compartments were radiocesium-free initially ($x_j(0) = 0$, all $j > 0$). Figure 4 shows results for the Combination V system. A similar graph was obtained for each of the other microcosms from which the data of Table 2 were then read off and computed.

Figure 4 illustrates general aspects of system behavior in these simulations under the influence of the constant "radiocesium" input. Three com-

Table 2. Equilibrium characteristics of compartments, and subsystems composed of equilibrated compartments.

	Compartments					
Combinations	Litter	Soil	Microflora	Millipedes	Leachate	Equilibrium Subsystems
Time to Equilibrium (days)						
I	264	—	—	—	∞	264
II	328	∞	—	—	∞	328
III	264	—	∞	—	∞	264
IV	168	∞	∞	—	∞	168
V	616	—	448	432	∞	616
VI	232	∞	186	168	∞	232
^{134}Cs Concentration (v)						
I	3.54	—	—	—	∞	3.54
II	3.52	∞	—	—	∞	3.52
III	3.52	—	∞	—	∞	3.52
IV	2.20	∞	∞	—	∞	2.20
V	5.10	—	1.01	0.93	∞	7.04
VI	2.28	∞	0.47	0.33	∞	3.08
Concentration Factors						
I	14.16	—	—	—	∞	14.16
II	14.08	∞	—	—	∞	14.08
III	14.08	—	∞	—	∞	14.08
IV	8.80	∞	∞	—	∞	8.80
V	20.40	—	4.04	3.72	∞	12.27
VI	9.12	∞	1.88	1.32	∞	5.76
Input (v day^{-1})						
I	0.13	—	—	—	0.13	0.26
II	0.13	0.13	—	—	0.003	0.26
III	0.13	—	0.06	—	0.07	0.26
IV	0.13	0.09	0.04	—	0.002	0.26
V	0.57	—	0.38	0.48	0.13	1.56
VI	0.44	0.13	0.36	0.22	0.02	1.17
Output (v day^{-1})						
I	0.13	—	—	—	0.00	0.13
II	0.13	0.00	—	—	0.00	0.13
III	0.13	—	0.00	—	0.00	0.13
IV	0.13	0.00	0.00	—	0.00	0.13
V	0.56	—	0.38	0.49	0.00	1.43
VI	0.45	0.00	0.35	0.22	0.00	1.02
Turnover (% day^{-1})						
I	3.70	—	—	—	0.00	3.70
II	3.70	0.00	—	—	0.00	3.70
III	3.60	—	0.00		0.00	3.60
IV	6.03	0.00	0.00	—	0.00	6.03
V	11.00	—	37.50	52.50	0.00	101.00
VI	19.89	0.00	75.00	66.00	0.00	160.89
Stability (%)						
I	21.60	—	—	—	—	21.60
II	18.08	—	—	—	—	18.08
III	23.44	—	—	—	—	23.44
IV	18.08	—	—	—	—	18.08
V	20.40	—	24.96	29.04	—	21.61
VI	10.43	—	12.23	10.64	—	10.02

partments—litter, microflora and millipedes—went through a transient response followed by a steady state. Soil and leachate never equilibrated because they are cesium sinks at the concentrations considered. Equilibrial characteristics of interest include (i) *time to equilibrium,* {days}; (ii) radiocesium *concentration,* {v}; (iii) *concentration factor,* a dimensionless property defined for present purposes as the ratio of compartment concentration to the voltage of the forcing function, 0.25 v; (iv) cesium *input flux* (input to compartment $j = \sum_i \lambda_{ij} x_i$), {v day^{-1}}; *output flux* (output of $j = \sum_i \lambda_{ji} x_j$), {v day^{-1}}; (vi) *turnover rate,* calculated for compartment j either as $\sum_i \frac{\lambda_{ij} x_i}{x_j}$ or as $\sum_i \frac{\lambda_{ji} x_j}{x_j} = \sum_i \lambda_{ji}$, {day^{-1}}; and (vii) *stability.*

Stability is the capacity of a system, subsystem, or compartment to minimize effects of a disturbance. To assess this for the six microcosms, the systems were disturbed after compartments which would equilibrate had reached equilibrium. This was accomplished by doubling the input to $\beta^{-1}\lambda_{01}x_0 = 0.5$ v sec^{-1} for 8 days and then returning it to its former level (Fig. 4: the driving function is doubled between 640 and 648 days). The disturbance caused a perturbation in equilibrated compartments (the nonsteady state ones were ignored; as cesium sinks they do not feed back to the remaining system and hence cannot affect it). Removal of the disturbance was followed by return to former equilibrium levels (Fig. 4: the graph shows deflections between 640 and 648 days, followed by recovery of equilibrated compartments—litter, microflora and millipedes—and of the subsystem comprised of these compartments). If $x_{j(\mathrm{eq})}$ is the equilibrium cesium concentration of compartment or subsystem j, Δx_j the perturbation of the same unit, $\delta_j t$ the duration of the perturbation, and $\Delta_j t$ the time for j to return to the original equilibrium (see Fig. 4), then a good measure of the stability of j is provided by $(x_{j(\mathrm{eq})})\ (\delta_j t)/(\Delta x_j)\ (\Delta_j t)$. This is because the less the disturbance, (Δx_j), relative to the equilibrium concentration, $(x_{j(\mathrm{eq})})$, and the more rapid the recovery time, $(\Delta_j t)$, relative to the duration of the disturbance, $\delta_j t$, the greater is the stability of j. The measure is dimensionless.

The following discussion will be limited to a general comparison of principal system differences which appear in the table.

Equilibration time.—Given a nonzero input, in order for a system, subsystem, or compartment to achieve a steady state it must also have an output which is nonzero. Thus, while soil and leachate in all of the microcosms studied had cesium inputs, they lacked outputs (Fig. 2, insets), and consequently never equilibrated (Table 2). Similarly, the microflora of Combinations III and IV accumulated radiocesium, but did not lose it. All other compartments eventually equilibrated at cesium levels defined by the equilibrium solutions of equations (1).

As shown in Table 2, the time to achieve this varied almost 4-fold, from 168 days for the litter of Combination IV and the millipedes of Combination VI to 616 days for the litter of Combination V (values to the nearest 8 days). Two general points illustrated by the tabulated data are that different compartments of the same microcosm and the same compartments in different microcosms take different periods of time to reach equilibrium.

Equilibrium Concentration of ^{134}*Cs.*—Compartments which do not equilibrate are indicated in Table 2 by "∞." Equilibrium concentrations, $x_{j(\mathrm{eq})}$, varied from 0.33 to 5.10 v in individual compartments, and from 2.20 to 7.04 v in subsystems composed of the steady state compartments. The litter value of 5.10 for Combination V is unusually high and more than double the equilibrium level of this compartment in Combination VI. The only difference between these two microcosms is that one contained soil. Since the environmental input to all of these systems was identical ($\lambda_{01}x_0 = 0.125$ v day^{-1}), the data of Table 2 indicate considerable variability in steady state cesium levels. This is a function of the components present and how they are coupled together.

Concentration Factors.—The observed range was 1.32 for millipedes in Combination VI to 20.40 for litter in Combination V. Since the driving function was constant, these figures are multiples (4×) of the equilibrium cesium levels. Expressed as concentration factors, though, they give some additional insights. The change in relative cesium-concentrating ability of *Dixidesmus* in Combinations V and VI can be interpreted in terms of the defining equations. The equilibrium solutions of equations (1) are

$$0 = \sum_i \lambda_{ij} x_{i(\mathrm{eq})} - \sum_i \lambda_{ji} x_{j(\mathrm{eq})} ,$$

signifying input = output,

$$\sum_i \lambda_{ij} x_{i(\mathrm{eq})} = \sum_i \lambda_{ji} x_{j(\mathrm{eq})} ,$$

and giving for the equilibrium concentration of compartment j

$$x_{j(\mathrm{eq})} = \left(\sum_i \lambda_{ij} x_{i(\mathrm{eq})}\right) \Big/ \sum_i \lambda_{ji} . \qquad (3)$$

Note (definitions p. 822) that the numerator is the compartment's input flux and the denominator its turnover rate.

The equilibrium equations for millipedes in Combinations V and VI are

$$\text{(V)}\ x_{4(\mathrm{eq})} = \frac{\lambda_{14}x_{1(\mathrm{eq})} + \lambda_{34}x_{3(\mathrm{eq})}}{\lambda_{41} + \lambda_{43}} = \frac{(0.020)\ (5.10) + (0.375)\ (1.01)}{0.475 + 0.050} = 0.92\ \mathrm{v}$$

$$\text{(VI)}\ x_{4(\mathrm{eq})} = \frac{\lambda_{14}x_{1(\mathrm{eq})} + \lambda_{34}x_{3(\mathrm{eq})}}{\lambda_{41} + \lambda_{42} + \lambda_{43}} = \frac{(0.045)\ (2.28) + (0.250)\ (0.47)}{0.250 + 0.160 + 0.250} = 0.33\ \mathrm{v}$$

Note that these values are almost identical to those given in Table 2, which were read off the computer output graphs. These calculations indicate, subject to the limitations of counting dead millipedes for radioactivity, as discussed earlier, that the equilibrium cesium concentrations—and hence the concentration factors for *Dixidesmus*—differ between Combinations V and VI. Correcting for loss to microflora through decomposition of the dead animals (i.e., assuming $\lambda_{43} = 0$), the concentration factors would still be different because $x_{4(\mathrm{eq})} = 0.29$ v in Combination V and 0.54 v in VI. In general, concentration factors for given compartments, j, would be expected to change in communities with different compartment compositions (different i's) as the input flux (numerator of equation 3), and possibly also the turnover (denominator), changed due to differences in the i's. This is borne out in Table 2 for all equilibrated compartments and subsystems.

Input and Output Fluxes.—Compartments, subsystems or systems in steady state with respect to a material have input = output. This is illustrated in Table 2. For equilibrated compartments in the six microcosms, inputs and outputs ranged from 0.13 to 0.56 v day^{-1}. For subsystems of equilibrated compartments, the input range was 0.26 to 1.56 v day^{-1}, and the output 0.13 to 1.43 v day^{-1}. These data illustrate the following points about material equilibria in coupled systems, all a consequence of network organization. Within a system, different compartments will tend to have different stationary input/output fluxes. Between systems driven by identical forcing functions, the same compartments may have quite different inputs and outputs. Therefore, the total flux of a material in a steady state system may vary considerably from that in another system which receives identical input from the environment.

Turnover.—The turnover rate of a compartment, j, is most easily computed as the sum of output rates, $\sum_i \lambda_{ji}$, rather than as the ratio of input flux to concentration, $\sum_i \frac{\lambda_{ij}x_i}{x_j}$. Turnover is thus equivalent to elimination rate. Calculations of turnover as $\sum_i \lambda_{ji}$ can be made directly from Table 1, and consequently are independent of the hypothetical simulations. The turnovers listed in Table 2, therefore, are real values for the experimental microcosms.

Table 2 indicates that each compartment tends to have higher turnover or elimination rates in systems with more compartments. This is because there are more compartments, i, from which to receive inputs in $\sum_i (\lambda_{ij}x_i)/x_j$, and to which to transfer outputs in $\sum \lambda_{ji}$. The result does not apply necessarily to compartments whose elimination is controlled by internal physiology, and the millipede data have already been qualified (p. 819, and footnote 2). The corrected daily millipede turnover rates are 47.5% in Combination V, and 41.0% in Combination VI. As more compartments are accrued in a system, total system turnover tends to increase. This is illustrated in the right-hand column of Table 2, and is consistent with general notions about energy and material flows in relation to ecosystem complexity.

Stability.—Data tabulated in Table 2 range from 10.43×10^{-2} to 29.04×10^{-2} for individual compartments, and 10.02×10^{-2} to 23.44×10^{-2} for the subsystems of equilibrated compartments. It is indicated that different compartments of a system can have different, although here generally similar, stabilities, and that the stability of cesium concentration in a given compartment varies from system to system. There appears to be no correlation between system complexity and ability to minimize and damp perturbations of radiocesium concentrations, which is contrary to inference from the stability theory of MacArthur (1955).

CONCLUSIONS

This investigation demonstrates that mineral kinetics in small laboratory microecosystems of limited complexity can be successfully modeled, and then their transient and stationary behavior studied comparatively with an analog computer. Environmental conditions and the compartments employed were the same for all systems, but the compartment combinations were different, and this was the principal experimental variable. It resulted in different patterns and degrees of intercompartmental coupling, producing radiocesium kinetics which were unique for each microcosm. The variable kinetics defined in turn variable system behavior. System and compartment attributes which changed with the nature of the coupling networks were duration of transient response, equilibrial cesium concentrations, concentration factors, input and output fluxes, turnover rates, and stability.

These results focus attention on the exceeding importance in natural, complex ecosystems of the organizational networks which define compartment interactions. Only one of numerous substances simultaneously transferred in the present microcosms, probably each with unique kinetics, was actually studied. Changes in the concentration or dynamics of any of these, especially major nutrients, would probably have altered the cesium kinetics. The multiplicity of material transfers and interactions conceivable in macroecosystems, together with the effects of intrasystem coupling as revealed in this investigation, make it apparent that to understand ecosystems ultimately will be to understand networks.

APPENDIX

Relationships between the microcosms and their models are as follows. Let

x_j ≡ radionuclide activity-density of compartment j, in appropriate units, $\{a\}$.
t ≡ real time, {days}.
λ_{ij} ≡ rate constant for transfer of radioisotope from compartment i to j, $\{t^{-1}\}$.
λ_p ≡ rate constant for physical radioactive decay $\{t^{-1}\}$; $\lambda_p = -0.0009$ day^{-1} for ^{134}Cs.
v ≡ {volts}.
α_j ≡ scale factor relating radioactivity to computer voltage for compartment j, $\{\mathrm{va}^{-1}\}$.
τ ≡ computer time, {sec}.
$\beta = \tau t^{-1}$ ≡ scale factor relating real time to computer time, $\{\text{sec day}^{-1}\}$.

The system equations (1), prior to being corrected for radioactive decay, would be

$$\dot{x}_j = \sum_i \lambda_{ij} x_i - \sum_i \lambda_{ji} x_j - \lambda_p x_j \,.$$

Correction of the primary data before curve-fitting eliminates physical decay from further consideration, both in determination of rate constants, and in simulations with the determined coefficients. In (1), both sides of each equation have the units $\{\mathrm{a}t^{-1}\}$. With voltage scaling, (1) becomes

$$[\alpha_j \dot{x}_j] = \sum_i \frac{\alpha_j(\lambda_{ij})[\alpha_i x_i]}{\alpha_i} - \sum_i \frac{\alpha_j(\lambda_{ji})[\alpha_j x_j]}{\alpha_j}$$
$$= \sum_i \left(\frac{\alpha_j}{\alpha_i}\right)(\lambda_{ij})[\alpha_i x_i] - \sum_i (\lambda_{ji})[\alpha_j x_j] \,,$$

and the new units are $\{\mathrm{v}t^{-1}\}$. The ratios (α_j/α_i) are input gains on integrators, and terms in brackets are scaled computer variables. Substituting $\beta\tau^{-1}$ for t^{-1} to achieve time scaling,

$$\beta[\alpha_j \dot{x}_j] = \sum_i \left(\frac{\alpha_j}{\alpha_i}\right)(\lambda_{ij})[\alpha_i x_i] - \sum_i (\lambda_{ji})[\alpha_j x_j] \,,$$

or

$$[\alpha_j x_j] = \sum_i \left(\frac{\alpha_j}{\alpha_i}\right)\left(\frac{\lambda_{ij}}{\beta}\right)[\alpha_i x_i] - \sum_i \left(\frac{\lambda_{ji}}{\beta}\right)[\alpha_j x_j] \,,$$

with units $\{\mathrm{v}\tau^{-1}\}$. Thus, the real systems, with units $\{\mathrm{a}t^{-1}\}$, are converted to computer systems with units $\{\mathrm{v}\tau^{-1}\}$.

When determining values of λ_{ij} in the Results section, voltage scale factors were $\alpha_i = \alpha_j = 10\mathrm{v}/100\%$ radioactivity $= 0.1\{\mathrm{va}^{-1}\}$. The time-scale factor was $\beta = 15$ sec/30 days $= \frac{1}{2}\{\tau t^{-1}\}$. The equations actually used instead of equation (2) were then

$$[0.1\dot{y}_j] = \sum_i 2(\lambda_{ij})[0.1 y_i] - \sum_i 2(\lambda_{ji})[0.1 y_j] \,,$$

where the y's are dimensionless.

In the simulations (Discussion), x_j was in arbitrary units, requiring no explicit scale factors, α_j. Computing time was $\tau = 600$ sec, representing a real time of 1200 days ($\beta = \frac{1}{2}\{\tau t^{-1}\}$). Scaled equations for all compartments except litter were

$$[\dot{x}_{j \neq 1}] = \sum_{i=1}^{5} 2(\lambda_{ij})[x_i] - \sum_{i=1}^{5} 2(\lambda_{ji})[x_j] \,.$$

For the litter, driven by a forcing function as input,

$$[\dot{x}_1] = \sum_{i=0}^{5} 2(\lambda_{i1})[x_i] - \sum_{i=1}^{5} 2(\lambda_{1i})[x_1] \,.$$

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BIOACCUMULATION OF RADIOISOTOPES THROUGH AQUATIC FOOD CHAINS*

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INTRODUCTION

With an increasing number of atomic energy installations and their associated problems of disposal of liquid wastes, we recognize that more and more aquatic environments are going to be exposed to at least low concentrations of radioactive materials. For the safety of human populations who may be drinking water which contains such radioactive materials, a set of maximum permissible concentrations has been recommended (International Commission on Radiological Protection, 1955). By themselves, however, such recommendations are inadequate to define completely the radiological hazard which may develop through aquatic food chains. Where biological systems are involved, the organisms may accumulate certain isotopes to many times the initial concentrations in the water. There are many radioisotopes, however, that apparently are not biologically concentrated.

This paper describes some of the mechanisms involved in the accumulation of radioisotopes by aquatic organisms, with special reference to food webs and metabolic rates, and presents some examples of how the concentration of radioisotopes in organisms can be used to measure relationships between different species.

THE ACCUMULATION OF RADIOACTIVE MATERIALS

In order to interpret the reasons for, or to predict the concentration of, radioactive substances in aquatic forms, the biologist must appreciate that several basic processes are involved. The most important are: (1) the mode of uptake, which includes adsorption to exposed areas, absorption into tissues, and assimilation of ingested material; (2) retention, which is a function of the biochemistry of the particular elements and components involved, the site of deposition, the turnover rate, and the radioactive half-life; and (3) the mode of elimination, which may involve ion exchange, diffusion, excretion, and defecation.

MODE OF UPTAKE

The metabolism of the different radioelements and the relative importance of the different modes of uptake will fluctuate widely between different species, environments, and seasons. While this paper is principally concerned with assimilation through food chains, the processes of adsorption and absorption of radioactive substances directly from the water cannot be neglected. They are primary mechanisms by which inorganic materials are acquired by aquatic plants which are the food sources of the animals. The absorption of radioisotopes of strontium, barium-lanthanum and sodium by fresh-water fish has been demonstrated by Prosser et al. (1945). Absorption of radio-calcium has been demonstrated by Lovelace and Podoliak (1952) and by Rosenthal (1956). Chipman (1956) showed that cesium readily passed through excised pieces of tuna skin but that there was little absorption of strontium or ruthenium from sea water. Fish immersed in effluent from the Hanford reactors concentrated Na^{24} in the tissues about 130-fold. Direct absorption of other isotopes which are dominant in the effluent, including Cr^{51}, Cu^{64}, P^{32}, As^{76}, and rare earths, appeared to be inconsequential, however. In fish that live downriver from the Hanford reactors, sorption of radioactive materials directly from the effluents accounts for only about 1.5 percent of the total radioactivity. Consequently, sorption is of much less importance than ingestion in the uptake of radioactive materials by Columbia River fish.

Adsorption occurs almost instantaneously, as has been demonstrated with yttrium on cells of the marine alga *Carteria* by Rice (1956), while equilibrium by absorption is usually reached by algal cells (Whittaker, 1953) and by vascular aquatic plants (Hayes, et al., 1952) within a few hours. Because of the rapid uptake of radioisotopes by these mechanisms, Columbia River plankton, composed almost entirely of diatoms, appears to reach equilibrium about one hour after floating into the zone containing effluent from the Hanford reactors (Foster and Davis, 1955).

Assimilation of ingested materials is the dominant means by which many radioactive materials become accumulated in animals since the bulk of their essential elements is obtained from their food. The contribution of food webs to the concentration of radioisotopes in aquatic animals was apparent from samples collected from the Columbia River soon after the first Hanford reactors began operation. Fish collected downriver from the reactors were approximately 100 times as radioactive as laboratory fish that were exposed to equivalent mixtures of the effluent, but fed uncontaminated food. Bottom animals, particularly herbivorous insect larvae, were found to be even more radioactive than the fish. The concentrations of radioactive materials in Columbia River organisms have never approached hazardous levels, however.

DIFFERENCES BETWEEN SPECIES

The relative concentrations of beta emitters in various Columbia River organisms are shown in Figure 1. There are several reasons for the differences

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Davis, J. J. and R. F. Foster, 1958. Bioaccumulation of radioisotopes through aquatic food chains. Ecology 39(3):530-535.

which occur between these species.

(1) Several radioisotopes are involved and their relative proportions are different in the various organisms. A good indication of the proportions of the several isotopes can be obtained from curves like those in Figure 2 which show the characteristics of the radioactive decay of the isotope mixtures peculiar to each species. The positions of the curves in Figure 2 at zero time approximate the relative concentrations of radioisotopes in the water, small fish [*Richardsonius balteatus* (Richardson)], caddis larvae [*Hydropsyche cockerelli*, Banks], and plankton of the Columbia River during late summer months. The predominance of short-lived isotopes in the water is shown by the steep slope of the bottom curve. Short-lived emitters also contribute most of the radioactivity in the plankton but these have virtually disappeared by the fifth day. The remaining activity in the plankton, which is only about 20 percent of that originally present, emanates from P^{32} and other isotopes with half-lives greater than two weeks. In the caddis larvae and fish, only about 5 percent of the initial radioactivity originates from short-lived emitters. After the first day the rate of decay is quite uniform and characteristic of P^{32} (half-life 14.3 days). The dominance of the P^{32} has been confirmed by radiochemical analysis.

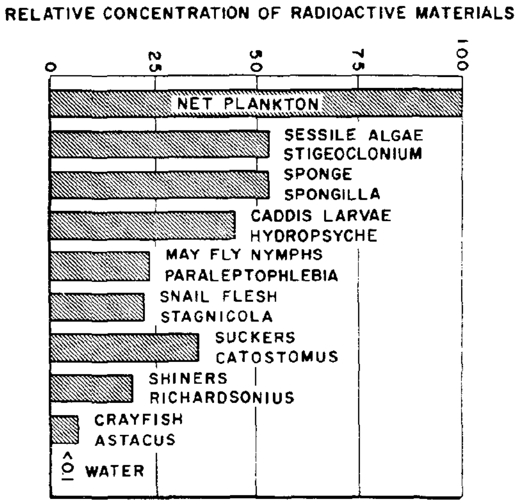

Figure 1 - Radioactivity in different Columbia River organisms.

The relative proportions of the several isotopes differ from one organism to another not only because of dissimilarities in the chemical composition and physiological demands of the different forms but also because of the different sorption characteristics which vary with morphology. Food chains are also important since they tend to "select for" isotopes of the essential elements, in this case P^{32}, and to "select against" nonessential elements. During the late summer months, the concentration of P^{32} in small fish of the Columbia River may be 165,000 time that of the water. On the other hand, As^{76} is barely detectable in the fish although it is responsible for a substantial fraction of the radioactivity in the water.

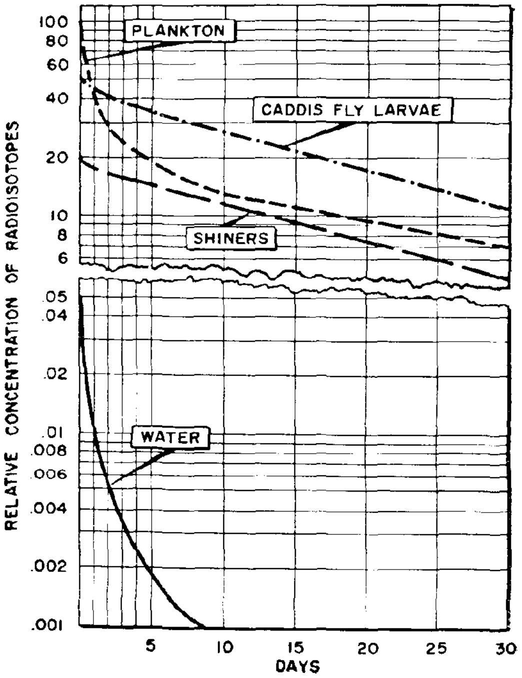

Figure 2 - Radioactive decay in different organisms and Columbia River water.

The marked variation in the relative abundance of different isotopes which can occur at different trophic levels and even between similar species has recently been pointed out by Krumholz (1956). From data collected at White Oak Lake, which received a variety of radioactive wastes from the Oak Ridge National Laboratory, Krumholz states: "Although radiophosphorus was generally accumulated in much greater amounts than any other radioelement by the organisms that served as food for the fish, that element made up only a small portion of the total radiomaterials concentrated in the fish tissues; whereas radiostrontium, which was present in the food organisms in only relatively small quantities, was accumulated in high concentrations in the fish skeletons. Furthermore, although the contents of the bluegill stomachs contained more radioactivity, on the average, than those of the black crappies, the crappies accumulated considerably greater amounts of radiomaterials in the hard tissues than the bluegills did. The bluegills, on the other hand, accumulated more radiomaterials in the soft tissues than the black crappies. Both species concentrated radiostrontium in quantities 20,000 to 30,000 times as great as those in the water in which they lived."

(2) Variation in moisture content between different organisms is a second reason for the differences in concentration of radioisotopes shown in Figure 1. Chemical composition is also a factor since we are

actually concerned with the quantity of a particular element in a unit mass of live tissue. The percentage of the live weight of the Columbia River plankton, caddis larvae, and minnows which is contributed by the inorganic ash is respectively 16, 2.2, and 3.0; and the concentration of phosphorus in the living organisms is about 150 ppm for plankton, 2,000 ppm for caddis larvae, and 6,000 ppm for minnows. Even greater differences may occur between the different tissues of an individual. Figure 3 shows how the concentration of radioactive materials varies between different tissues of whitefish in the Columbia River. Since virtually all of the activity is from P^{32} this gives a good indication of the relative concentration of phosphate in the different tissues.

(3) A third reason for differences in concentrations of radioisotopes between different organisms is their relative position on the food pyramid. Although elements are exchanged continuously between the water and the organisms of a food web, there is a mean retention time for each element in each organism. Each trophic level thus serves as a kind of pool or reservoir in which essential elements are retained for some mean length of time before they are passed on to the next level. The size of each pool will be governed by the total amount of an element held by the entire biotic mass making up the particular trophic level. A major fraction of most radioactive contaminants accumulated by aquatic life will be held by the plankton and benthic algae because of their relatively large total mass. Rigler (1956) found that over 95 percent of the P^{32} added to a lake was taken up by plankton (including bacteria) within 20 minutes. But retention time is not necessarily a function of the size of the pool. Indeed it is more apt to be inversely related since most elements will remain for a longer time in the larger organisms than in the small plant forms, although the small plants constitute the largest pool. Since, in the Columbia River, we are dealing with a flowing stream where isotopes are added at a more or less constant rate, much of the mineral exchange system can be considered as a once-through process rather than a cycle. Some radioactive decay will occur while the isotopes are retained in each trophic level. This decay, and thus the effective retention period, should be measurable by a progressive decline in specific activity -- the concentration of an isotope per unit mass of the element. For example, under certain conditions midge larvae in the Columbia River may contain on the order of 4 μc P^{32}/g of P and the small fish which eat the midge larvae about 0.5 μc P^{32}/g of P . Since the half-life of P^{32} is two weeks, the phophorus deposited in the fish must be, on the average, about six weeks "older" than that in the midge larvae. The reltive "age" of the isotope will differ between species and differ between species and will change with the age, sixe, and growth rate of the individual and with the seasons. The decrease in specific activity will, of course, be more apparent for short-lived isotopes than for those with half-lives of several weeks or more.

The specific activity of the river biota should be appreciably lower than that of the water not merely because of the time required to incorporate the isotope into the organisms but also because of the "pools" of elements fixed in the biota and sediments. When a radioisotope is first introduced into a body of water it will be isotopically diluted with the stable form of the element which is dissolved in the water. Soon, it also will become isotopically diluted by exchange with the stable form of the element which has not been in solution. With a single addition of isotope into a "static" environment, the specific activity will eventually become uniform throughout the biota. Reservoirs of phosphates in the solids of lakes have been described by Hutchinson and Bowen (1950) and Hayes and coworkers (1952), who have studied phosphorus exchange with the use of P^{32} .

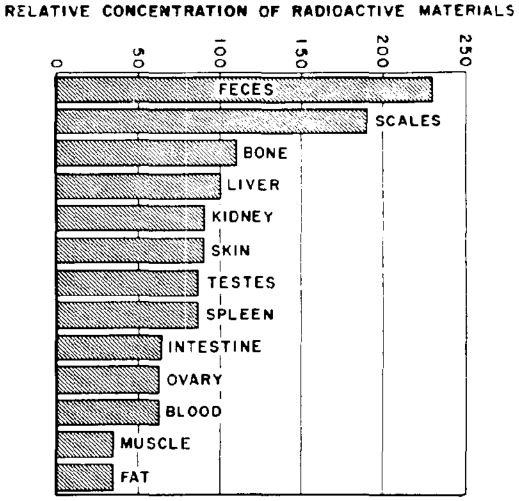

Figure 3 - Radioactivity in different tissues of Columbia River fish.

RATE OF ACCUMULATION BY AQUATIC ORGANISMS

The nearly instantaneous uptake of isotopes by adsorption and the rapid uptake by absorption have been mentioned. When animals are chronically feeding on radioactive materials, the rate at which their concentration of the isotopes approaches equilibrium will be a function of the radioactive and biological half-lives of the particular isotope involved.

Figure 4 shows the rate at which caddis fly larvae (Hydropsyche cockerelli) accumulated radioactive materials (mostly P^{32}) when fed filamentous algae (mostly Spirogyra) that had been cultured in reactor effluent. If there was no biological turnover of phosphorus in the caddis larvae, the time required to reach some fraction of the equilibrium level would be a function of the radioactive decay constant and could be predicted from the equation:

$$\frac{Q_t}{Q_e} = 1 - e^{-\lambda t}$$

where Q_e is the amount of the isotope present at equilibrium, Q_t is the amount present at some time (t) before equilibrium is reached, and λ is the radioactive decay constant.

Since true equilibrium will only be reached after infinite time, we can consider practical equilibrium to occur when $Q_t = 0.9\,Q_e$, and solve the equation for t. For any isotope, t will be equal to the half-life multiplied by $\frac{-ln\,0.1}{.693}$. For P^{32} it is approximately 47 days.

The curve presented in Figure 4 shows a much shorter time which indicates that significant biological turnover is present. The equation is easily modified to take this into account:

$$\frac{Q_t}{Q_e} = 1 - e^{-\delta t}$$

where δ is the sum of λ and β, where β is the constant for biological half-life. A 0.9 of equilibrium,

$$t = \frac{-ln\,0.1}{\beta + \lambda}$$

From Figure 4, t is about 50 hours and

$$50 = \frac{2.302}{\frac{.693}{T_b} + \frac{.693}{343}}$$

(343 is the half-life of P^{32} in hours).

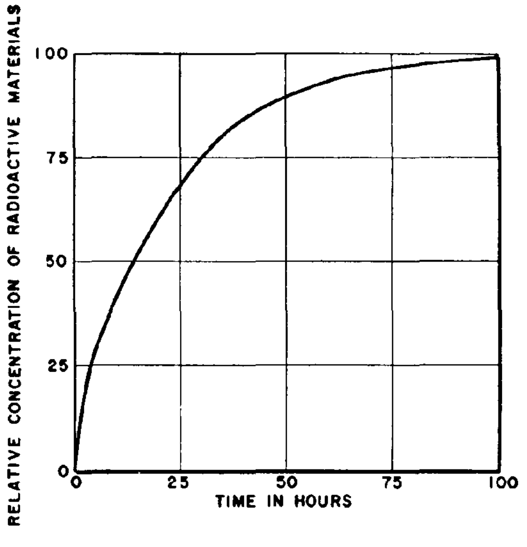

Figure 4 - Rate of accumulation of effluent isotopes by caddis fly larvae.

The biological half-life, T_b, is about 16 hours. Under such conditions the specific activity of the P^{32} will not diminish appreciably at this trophic level.

If laboratory tests can be carried out in conjunction with field observations, some interesting ecological relationships can be deduced. For example, we might measure the concentration of P^{32} in small minnows collected from a contaminated environment and find this to be $2 \times 10^{-3}\,\mu c/gram$. If the average size of the minnows was 5 grams, then each fish would have a body burden of about $10^{-2}\,\mu c$ of P^{32}. From a laboratory test, which duplicated field conditions as closely as possible, we might find that 0.9 of Q_e was reached in 20 days. Then

$$\delta = \frac{-ln\,0.1}{t} = \frac{2.302}{20} = 0.115$$

The same test might show that half of the ingested P^{32} was assimilated and deposited ($a = 0.5$). Assuming the concentration of P^{32} in the river fish to be in equilibrium with the environment and neglecting growth.

$$Q_e = \frac{aq}{\delta}$$

where q is the quantity of P^{32} ingested per unit time -- in this case each day. Then,

$$10^{-2}\,\mu c = \frac{0.5\,q}{0.115}$$

and

$$q = 2.3 \times 10^{-3}\,\mu c/day.$$

In order to have reached the observed concentration of P^{32}, each minnow must have consumed about $2.3 \times 10^{-3}\,\mu c$ of P^{32} each day. If, from stomach analyses, we have found that the fish feed predominantly on midge larvae and from field collections we have found that the midge larvae have a concentration of P^{32} of about $10^{-2}\,\mu c/g$, then we can surmise that each minnow has been eating about 0.23 grams of the midge larvae each day.

SEASONAL VARIATIONS

Since most aquatic animals are poikilothermic, their metabolic rates, and thus their feeding rates, change with variations in temperature and so with the seasons. For those aquatic forms that accumulate radioactive substances principally via ingestion, the concentration of radioisotopes fluctuates with metabolic rate. Figure 5 shows the seasonal fluctuations which occur in the radioactivity of plankton (diatoms) and minnows (Richardsonius balteatus) in the Columbia River. Fluctuations in plankton are quite similar to those in the water since the radioisotopes are acquired by direct absorption and adsorption (Foster and Davis, 1955). On the other hand, fluctuation in the radioactivity of the minnows is more closely related to the temperature. The 75-fold increase in concentration of radioisotopes in the fish between winter and late summer does not mean simply that the fish are eating 75 times as much food. The seasonal fluctuations result from the interaction of all of the factors mentioned above which influence the accumulation of radioactive materials. As the feeding rate increases for each organism, its intake of radioisotopes may be disproportionately large. The consumer is not only eating more grams of food, but each food organism has become more radioactive, and the effective time intervals between trophic levels have become less. Possibly the food habits of the species in question have also changed. A complete evaluation of the seasonal fluctuations in any one species would require an immense amount of work, not only on the food habits of the species but also on its physiology and on the radioactive contamination of its food organisms.

Not all seasonal variations are associated merely with temperature since deviations may occur where complex life cycles are involved. This occurs in immature insects which are less radioactive during quiescent periods than when the larvae or nymphs are feeding. It is also true of salmon that return to the Columbia River to spawn. The adult salmon virtually stop feeding when they enter fresh water, and consequently pick up very little radioactive material. Krumholz (1956) also observed definite seasonal changes in the accumulation of radiomaterials by fish of White Oak Lake. These corresponded to some extent with seasonal changes in temperature. He noted, however, that the accumulation of radioisotopes in black crappie and bluegills stopped at the first of August when the temperature reached about 80° F. He attributes the rapid loss of radioactive materials during August and September to a period of summer dormancy for these species.

SUMMARY

Some radioactive materials introduced into aquatic environments may be accumulated by the organisms. The amount of accumulation will vary over many orders of magnitude depending upon the kinds of isotopes involved and many physical, chemical, and biological factors. Such concentration is of considerable importance in the control of radiological hazards and the aquatic biologist has definite responsibilities in this area.

The processes of adsorption and absorption are of major importance in the uptake of radioisotopes by plants but appear to be of less importance than the food chain in the uptake by aquatic animals. The concentration of radioactive substances will vary between species and tissues and will fluctuate according to food habits, life cycles, and seasonal changes.

Within the biotic mass, a major fraction of most radioactive contaminants will be held by the organisms which make up the primary trophic levels. In a flowing stream, the specific activity of a radioisotope will diminish along the food chain. Where the turnover rates of certain isotopes can be measured, inferences can be drawn on feeding habits.

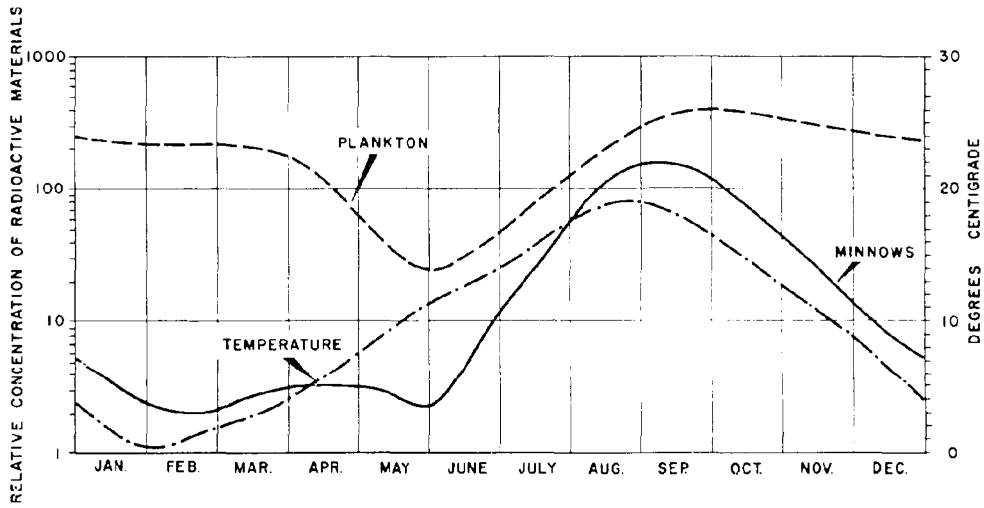

Figure 5 - Seasonal fluctuations in radioactivity of Columbia River organisms.

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RADIATION ECOLOGY IN FRESHWATER COMMUNITIES

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Since our waters seem destined to be used as disposal receptors of our society's waste products, they will, no doubt, receive their share of radioactive wastes as uses of nuclear energy increase. Today, I would like to discuss some of the aspects of radiation ecology and radionuclide cycling in the freshwater environment.

Two reasons why people are interested in radionuclides in water are: (1) from a health-safety aspect, radioactive wastes must be monitored to insure that undesirable amounts of radioactive elements are not passed through food-webs to man, and (2) radioactive nuclides are excellent tracers to use in scientific investigations. I will devote my remarks today to the latter aspects, that of using radionuclides as tools for ecological research.

RADIONUCLIDES IN THE ENVIRONMENT

There are four sources which may contribute radionuclides to freshwaters, and these contributions vary in composition and amounts. The first source is that of the naturally occurring radionuclides including ^{238}U, ^{226}Ra, ^{232}Th, ^{40}K, ^{14}C, ^{210}Po and ^{210}Pb. These may be found in concentrations ranging from 10^{-9} to 10^{-10} μCi/ml (μCi = 1×10^{-6} curies; curie = quantity of a radioactive nuclide disintegrating at the rate of 3.700×10^{10} atoms per second). In some of the radium hot springs, concentrations may reach 10^{-4} μCi/ml. A second source of radionuclides in water is from the disposal of wastes from users or producers of nuclear energy.

Cushing, C.E. 1970. Radiation ecology in freshwater communities. pp. 45-56. In: Man and Aquatic Communities. (Anonymous). Seminar conducted by Water Resources Research Institute, Oregon State University, Corvallis, Oregon, Spring Quarter 1970.

These include AEC facilities such as Hanford, Oak Ridge, and Savannah River; wastes from experimental use in laboratories and institutions throughout the country; by-products of the use of radionuclides for medical purposes; and disposal of wastes from nuclear powered vessels and fuel processing plants. Radionuclides from these sources include the fission products ^{89}Sr, ^{90}Sr, ^{91}Y, ^{95}Zr-Nb, ^{106}Ru, ^{131}I, ^{137}Cs, ^{140}Ba, ^{144}Ce and the rare earths; and neutron activated radionuclides including ^{32}P, ^{46}Sc, ^{51}Cr, ^{54}Mn, ^{55}Fe, ^{59}Fe, ^{57}Co, ^{65}Zn, ^{64}Cu, ^{76}As, ^{24}Na, and others.

The abundance of the radionuclides from these sources, of course, is quite variable. In most cases, radioactive decay and dilution reduce the great majority to negligible amounts in our waters. A third source of radioactivity in the environment, and one getting much publicity now, is from releases from such sources as power reactors, experimental facilities, etc. The composition and abundance from this source obviously depends on the nature of the release.

The fourth source of radionuclides in water is from fallout from weapon testing detonations. The radionuclides produced include both fission products and neutron activation radioisotopes. The composition is dependent upon (1) the physical construction of the device, i.e. the materials it is made of, and (2) the environmental characteristics at the detonation site, i.e. underground, surface, air, or underwater detonation.

The relative distribution of radionuclides in the environment is governed, as would be expected, by many interrelated factors just as are the stable elements in an ecosystem. The nature of the particular water body, its biotic and abiotic constitutents, and the characteristics of the radionuclides all influence the fate of a given isotope.

Rigler (1956) found that ^{32}P added to a lake was very rapidly taken up by the bacteria and phytoplankton and in time was associated with the sediments. The degree of eutrophication of a water body will influence the distribution of a given radionuclide through isotope dilution. An added amount of ^{32}P is more likely to be rapidly taken up by algae in an oligotrophic lake low in nutrients than in an eutrophic one with an excess of phosphorus.

It must be kept in mind that there is basically no discrimination by an organism between radioactive and stable isotopes of the same element. The chemical state of a particular radionuclide is also important. Trivalent ^{51}Cr occurs in the dissolved state whereas hexavalent ^{51}Cr is present as a particulate.

Table 1, from Brungs (1967), shows the relative distribution of four radionuclides introduced into experimental ponds as measured over a time period of 80 days. Note how the great majority of the added material was eventually associated with the sediments.

Table 1. Percentage distribution of ^{60}Co, ^{65}Zn, ^{85}Sr and ^{137}Cs in the dissolved, particulate, biota, and substrate fractions of experimental ponds (day 2 - day 80). (after Brungs 1967).

	Dissolved	Particulate	Biota	Substrate
^{60}Co	15 - 0.7	43 - 0.3	0.2 - 0.05	41.8 - 98.9
^{65}Zn	16 - 0.1	25 - 0.5	0.5 - 1.0	58.5 - 98.4
^{85}Sr	83 - 23	1.0 - 0.1	0.1 - 0.4	15.9 - 76.5
^{137}Cs	13 - 0.3	5.4 - 0.3	0.2 - 0.03	81.4 - 99.4

MINERAL CYCLING IN AQUATIC ENVIRONMENT

Before proceeding with this subject, it might be useful at this point to explain some of the terms used in presenting radioecological data. Probably the most widely used expression is that of "activity density" which is the absolute concentration of a particular radionuclide per some unit of biomass, time, area, etc.

Examples of these would be disintegrations per minute/mg, pCi/ml (picocurie = 1×10^{-12} curie), μCi/fish, or, if a rate is involved, counts per minute/mg/hr. A second commonly used expression is the concentration factor, which is supposed to be an indication of the ability of the organism in question to concentrate a particular radionuclide over that of the ambient concentration.

It is the ratio of the radioactivity per gram wet weight of the organism to the radioactivity per ml of water. There is a good deal of discussion currently as to the validity of this measurement, as it has been widely used and misused in the literature. It is accurate only when the organism is in equilibrium with the water and is dependent upon the radionuclide concentration in the water. Concentration factors generally decrease from lower to higher trophic levels because of radioactive decay, mode of uptake, and turnover rates.

The third, and ecologically the best, method of expression is termed "specific activity", and is defined as the ratio of the radioactive to stable concentration of an element in an organism. Under certain assumptions, it is a true indication of an organism's demand from the environment and is useful in predicting the accumulation of an element by an organism.

The criteria for using specific activities are: (1) that the stable and radioactive isotopes must be completely mixed and the rate of biological movement the same; (2) the biological half-life of the element is known for the particular organism or tissue; (3) the organism is exposed to the same concentrations and is in equilibrium; (4) the concentration of the stable isotope in the environment is known; and (5) the chemical forms of the stable and radioactive isotopes must be similar.

For example, an uptake of 3 pCi of ^{65}Zn per gram by an organism containing 150 μg of zinc per gram would be ecologically equivalent to the uptake of 9 pCi of ^{65}Zn per gram by an organism containing 450 μg of zinc per gram. The use of activity densities alone would present a misleading interpretation. For a fuller discussion of this, see Nelson (1964).

The cycling of radionuclides in the aquatic environment is basically an interaction between the biological demand of the organisms and the mineral composition of the media, and differs from isotope to isotope. In this respect, it is no different from cycling of the stable isotopes of the same elements, but, in many cases, is much easier to measure.

In discussing radionuclide cycling, there are six factors or aspects, which we will consider: (1) the mode of uptake, (2) rates of uptake, (3) retention-elimination, (4) food-web relationships, (5) environmental effects, and (6) dispersal of radionuclides.

MODE OF UPTAKE

There are essentially, two principal modes of uptake of radionuclides by organisms: (1) absorption, which includes metabolic uptake or assimilation, and (2) adsorption, including ion-exchange or other physical phenomena taking place on the exterior surface of the organism.

Metabolic uptake by autotrophic organisms is related to photosynthesis and mineral assimilation for the elaboration of new organic material. The relative amount of metabolic uptake by zooplankton is related to the specific radionuclide. For instance, in zooplankton metabolic uptake is the principal mode for the accumulation of ^{85}Sr which is incorporated in the exoskeleton.

On the other hand, little ^{32}P is assimilated by zooplankton from food, most of it passing through in the feces and ending up in the sediments. Larger benthic invertebrates also exhibit a selective uptake irrespective of ambient concentrations.

The five most abundant radionuclides in Hydropsyche cockerelli larvae, in descending order, were ^{32}P, ^{64}Cu, ^{51}Cr, ^{65}Zn, and ^{24}Na. The five most abundant radionuclides in the water, in descending order, were: ^{64}Cu, ^{239}Np, ^{24}Na, ^{56}Mn, and ^{51}Cr (Davis 1965). Note that ^{32}P and ^{65}Zn were first and fourth highest in the larvae, but not in the highest five in the water. Kormondy (1965) studied the accumulation of radionuclides by larval Plathemis lydia and found that very little of the zinc accumulated was assimilated and most was adsorbed in the surfaces.

Adsorptive uptake by autotrophic organisms, phytoplankton and periphyton, is very important and is directly related to their large surface to volume ratio. Adsorption may be a first step followed by metabolic uptake through the cell walls. Cushing and Watson (1968) investigated the uptake of ^{32}P and ^{65}Zn by floating living and killed phytoplankton through the Columbia River in the vicinity of the Hanford effluents.

We surmised that if we subtracted the uptake of the killed plankton from that of the living, the difference should be metabolic uptake. Statistical analyses of the results, however, showed that killed plankton accumulated significantly more ^{65}Zn than did living plankton, and, conversely, living plankton accumulated more ^{32}P than did the killed.

After the initial shock wore off, we found that our results agreed with other workers who had found enhanced ^{65}Zn uptake by killed algae (Gutknecht 1963, Bachmann 1963). Our laboratory studies of ^{65}Zn uptake by natural periphyton communities show that there is little difference in uptake by living communities in continuous light or darkness or by killed communities - again emphasizing the importance of adsorptive uptake.

High levels of the biologically nonessential elements such as ^{51}Cr, ^{239}Np, and ^{46}Sc are accumulated by Columbia River plankton and periphyton. Zooplankton accumulate large amounts of ^{32}P by adsorption and may be related to epizootic bacteria on the animals integument (Rigler 1961). ^{85}Sr adsorption, however, is insignificant.

RATES OF UPTAKE

The rate of uptake of a particular radionuclide is a function of many factors. Body size (surface to mass) is generally inversely related to the rate of uptake. The biological demand for a given element is obviously important when comparing rates; consideration of the pre-nutritional history of the organism is important in this aspect.

The position of an organism in the food-web and its metabolic rate also govern the rate of uptake. In general, the further one proceeds through the trophic levels, the slower is the rate of uptake. Finally, a host of environmental factors,which will be discussed subsequently, play an important regulating role. The interplay of these factors must be considered, i.e. phytoplankton have a negligible demand for chromium, but exhibit a rapid uptake rate of it by virtue of adsorption to the large surface area present.

RETENTION - ELIMINATION

A knowledge of the retention of a particular radionuclide is fundamental to studies of food-web cycling and the construction of meaningful models to describe ecosystem dynamics. Retention studies involve estimates of elimination and turnover rates of the element in question. Radionuclides accumulated by an organism are lost by two ways: (1) biological turnover ($T_b 1/2$), and (2) physical decay ($T_p 1/2$).

The time it takes for the initial radionuclide burden to decrease by 50% by these two factors is known as the effective half-life, $T_e 1/2$. Using this information in conjunction with the activity density in the organism and its food at two successive sampling periods, good estimates of the amount of food eaten can be calculated. Some estimates of these measurements for rainbow trout are: ^{137}Cs $T_b 1/2$ = 25-80 days, (Häsänen et al. 1967), ^{65}Zn $T_e 1/2$ = 134 days (Nakatani 1966), and ^{32}P $T_e 1/2$ = 12 days (Watson et al. 1959).

FOOD-WEB RELATIONSHIPS

The definition of food-web relationships is one of the most effective uses of radionuclides by ecologists. With proper use, a knowledge of what element goes where and at what rates can be ascertained. One generalization which has been made is that the higher and faster the uptake by a particular organism, the greater is its response to changing environmental conditions.

Ball and Hooper (1963) spiked a stream with ^{32}P and found that uptake and cycling rates were faster in the periphyton, next in the filter feeders and algae scrapers, slower in the omnivores, and slowest in carnivores.

Other radionuclides, for instance ^{137}Cs, behave differently. Davis (1965) states that the location in the food-web affects the amount of radionuclides accumulated and that it is dependent upon: (1) the time required for the isotope to reach the organism from the water, (2) accumulation efficiency and transport time of radionuclides are, in turn, dependent upon the metabolic demand and the biological turnover rate ($T_b 1/2$) of the element for each component of the food-web, and (3) the degree to which transport time influences the efficiency of transfer depends upon the physical half-life of the radioisotope involved.

ENVIRONMENTAL EFFECTS

The influences of environmental factors on these processes are many and varied, and, obviously, are not unique to radioisotopes but pertain to stable elements as well. Responses, however, are usually easier and more accurately measured with tagged elements. Since there is a wealth of such data available, I would like to just present a few examples of data from studies using radionuclides to investigate physical, chemical, and seasonal phenomena.

Harvey (1969) found that non-lethal temperature increments up to 40 C. had no effect on the uptake of several radionuclides by a blue-green alga. Whitford and Schumacher (1961) used ^{32}P to show the enhanced uptake by lotic algae in flowing water as compared to standing water. Work in our laboratory and elsewhere has shown a stimulatory effect of light upon ^{65}Zn uptake by algae.

Bachmann and Odum (1960) thought this might be related to photosynthesis, but Gutknecht (1961, 1963) and we believe it is more directly related to pH changes; ^{65}Zn adsorption is highly pH dependent. The uptake of ^{85}Sr by algae has also been shown to be light related although the exact mechanism is not clear Patten and Iverson (1966). Kormondy (1965) showed that ^{65}Zn uptake by dragonflies is independent of temperature.

A temperature - dependent uptake of several radionuclides, however, has been shown for several organisms in the Columbia River.

Influences of the chemical constituents in the environment are, of course, very complex and highly dependent upon the element in question. Many workers have shown that there is a direct correlation between uptake of a radionuclide and its ambient concentration. We have found that decreasing the ambient concentration of ^{65}Zn by 50% decreases the uptake by periphyton by a corresponding amount.

The isotopic dilution, or ratio of stable to radioactive ions in the water, influences the rates and amount of uptake. Caddisfly larvae, diatoms, and juvenile suckers have been shown to take up more ^{32}P from water low in stable P than from one with a high stable P content (Davis 1965). Not only can there be isotopic dilution by the same ion, but also between similar stable and radioactive ions. We have found that uptake of ^{65}Zn by periphyton is decreased if the number of stable zinc ions in Columbia River water is doubled (0.036 ppm to 0.072 ppm), and that uptake of ^{65}Zn is drastically reduced if the number of stable magnesium ions is doubled (3.6 ppm to 7.2 ppm).

This is evidence of a competition for binding sites by divalent cations. Brungs (1965), studying bluegills, found that a 100 times increase in the calcium content of the water decreased the uptake of ^{85}Sr by a factor of about 20 times. The effect of pH varies among elements; ^{65}Zn uptake increases with an increase in pH, ^{90}Sr uptake increases with a decrease in pH, and ^{90}Y, a daughter isotope of ^{90}Sr, uptake decreases with a decrease in pH.

Seasonal influences of radionuclide cycling are essentially a reflection of physical and chemical changes interacting over a period of time, and we need not go into much detail.

An example of this can be seen in Fig. 1 (Cushing 1967). The upper graph shows the concentration of ^{32}P and ^{65}Zn in net plankton on a $_{n}$Ci/g dry wt. basis and shows a marked decrease in summer when the reactor effluents are greatly diluted by the spring runoff. The lower graph shows that despite the low activity density in summer, more associated radioactivity is transported because of the high biomass levels.

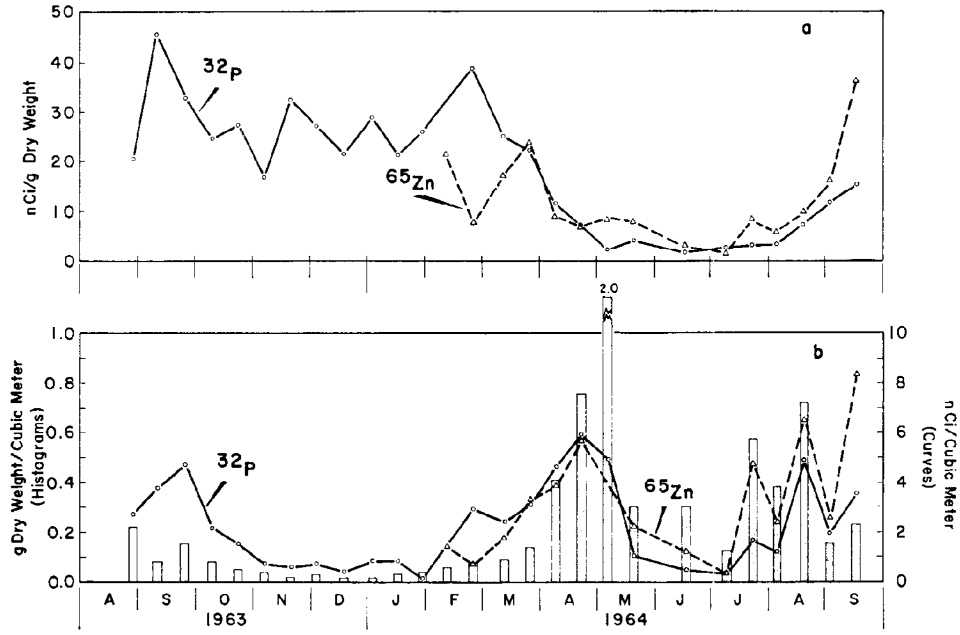

FIG. 1. a. Concentration of ^{32}P and ^{65}Zn by net plankton. b. Concentration of net plankton and associated ^{32}P and ^{65}Zn in water.

DISPERSAL OF RADIONUCLIDES

Dispersal of radionuclides is important ecologically and from a health-safety view. The health-safety aspect is really a subject of its own and I do not have the competency to discuss it in full detail. Ecologically, radionuclides can provide us with a wealth of information, given the proper experimental design, whether they are "spiking" studies or ones using radionuclides already in the environment such as fallout or waste products.

Data on fish migration (Watson 1966), mineral translocation within the water mass, feeding habits (Kevern 1966), and migration of emergent insects with aquatic larval stages (Coutant 1967) are just a few of the many ecological studies performed with radioactive tracers.

SUMMARY

In conclusion, the presence of radioactive isotopes in the freshwater environment, disregarding their source, can provide us with a wealth of ecological data. Information ranging from the movement of a single element from one organism to another, or from one tissue to another, to data helping to unsort the complexities of entire aquatic foodwebs can be gained with properly designed experiments and treatment of the data. The dynamics of radionuclide cycling are basically no different from their stable counterparts, but their value lies in the increased precision of measurement, particularly at concentrations too low to measure by standard analytical procedures.

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RADIOACTIVITY IN THE SEA

GENERAL CLASSIFICATION OF RADIONUCLIDES

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General

Radionuclides in the marine environment can: (1) remain in solution or in suspension; (2) precipitate and settle on the bottom; or (3) be taken up by plants and animals. Certain factors interact to dilute and disperse these materials, while other factors simultaneously tend to concentrate them. Currents, turbulent diffusion, isotopic dilution, and biological transport dilute and disperse radionuclides. Concentrating processes may be biological, chemical or physical. Radionuclides are concentrated by the biota, by uptake directly from the water, and by passage through food webs; they are concentrated chemically and physically by adsorption, ion exchange, co-precipitation, flocculation, and sedimentation. Also, radionuclides in the sea are cycled through the water, sediment, and biota (Fig. 1). This cycling can be described by the three R's: routes, rates, and reservoirs.

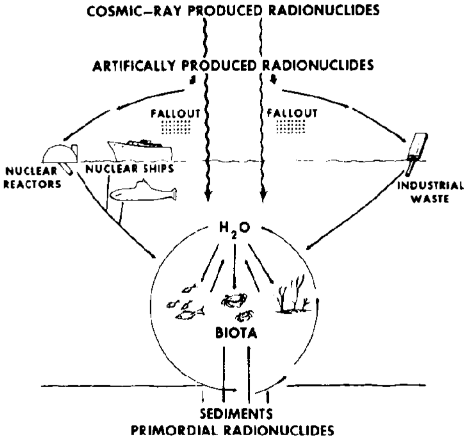

Fig. 1. Naturally occurring radioactivity, consisting of cosmic-ray produced and primordial radionuclides and artificially produced radionuclides, are continuously being cycled through the three components of the marine environment—water, biota, and sediments.

Each radionuclide tends to take a characteristic route and has its own rate of movement through the three components (reservoirs) of the marine environment. Radionuclides are exchanged from the water to the sediments or to the biota. In effect the sediments and biota compete for the isotopes in the water. Even though in some instances sediments initially remove large quantities of artificial radionuclides from the water and thus prevent their immediate uptake by the biota, this sediment-associated radioactivity may later affect many benthic organisms by exposing them to radiation. Also, radionuclides leach from the sediments back to the water and again become available for uptake by the biota. Even before radionuclides are leached from the sediment they may become available to the biota, due to variation in the strength of the bonds between the different radionuclides and the sediment particles. Loosely bound radionuclides can be "stripped" from particles of sediment and utilized by bottom-feeding organisms.

Classification of Radionuclides

Naturally occurring radionuclides. Naturally occurring radionuclides in the oceans, at least in part, arose from the weathering of rock. The principal categories of natural radionuclides are: (1) primordial radionuclides and their decay products (daughters); and (2) radionuclides resulting from reactions between cosmic-rays and elements in the atmosphere or in the earth.

Several long-lived naturally occurring radionuclides have been identified (Table 1). Most of the natural radiation in the sea originates from three of these: uranium 238, thorium 232, and potassium 40, the latter accounting for more than 90% of the natural radiation. The decay of potassium 40 ends with its transformation into stable calcium or argon, whereas uranium and thorium decay into a long series of radioactive "daughter" elements. Most potassium compounds are soluble in seawater and potassium ions are adsorbed on particles of clay, sediments, and other materials with an ion-exchange potential. Since uranium precipitates more slowly than thorium, its concentration reaches high levels in seawater (Ref. 1). The chemical trans-

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Rice, T. R. and T. W. Duke. 1969. Radioactivity in the sea: general classification of radionuclides. pp. 566-570. In: The Encyclopedia of Marine Resources. (F. E. Firth, ed.). Van Nostrand Reinhold, New York, New York.

TABLE 1. PRINCIPAL NATURALLY OCCURRING RADIONUCLIDES IN THE SEA

Nuclide	Half-life (years)	Concentration (g/l)	Concentration ($\mu\mu$c/l)
Tritium	1.2×10^{1}	3.2×10^{-18}	3.0
Beryllium 10	2.7×10^{6}	1.0×10^{-13}	2.0×10^{-3}
Carbon 14	5.5×10^{3}	3.1×10^{-14}	1.5×10^{-1}
Silicon 32	7.1×10^{2}		1.2×10^{-5}
Potassium 40	1.3×10^{9}	4.5×10^{-5}	3.0×10^{2}
Rubidium 87	5.0×10^{10}	3.4×10^{-5}	2.8
Radium 226	1.6×10^{3}	8.0×10^{-14}	$(3.6–.25) \times 10^{-2}$
Thorium 228 (RdTh)	1.9	4.0×10^{-18}	$(0.25–1.4) \times 10^{-2}$
Radium 228 (MsTh)	6.7	1.4×10^{-17}	2.3×10^{-3}
Thorium 230 (Io)	8.0×10^{4}	6.0×10^{-13}	$(0.4–1.2) \times 10^{-2}$
Protactinium 231	3.2×10^{4}	5.0×10^{-14}	$(1.4–2.4) \times 10^{-3}$
Thorium 232	1.4×10^{10}	2.0×10^{-8}	$(0.02–1.0) \times 10^{-2}$
Uranium 235	7.1×10^{8}	1.4×10^{-8}	5.2×10^{-2}
Uranium 238	4.5×10^{9}	2.0×10^{-6}	1.15

formation of decaying uranium has some interesting effects. Salts of thorium 230 (the second long-lived daughter of uranium 238), like those of thorium 232, precipitate rapidly into the marine sediments which are being formed continuously. Precipitated thorium 230 eventually decays into radium 226, which partially dissolves and is carried upward in the water where its concentration progressively diminishes toward the surface. The concentration of radium 226 in the water thus provides an index of the mixing of the water.

Several radionuclides are produced in the upper atmosphere by cosmic rays, the most energetic radiations known. Primary cosmic rays originate outside the earth's atmosphere and secondary cosmic rays are produced by interactions between primary cosmic radiation and elements in the earth's atmosphere or in the earth itself. The nuclei of nitrogen, oxygen, and other atmospheric gases react with cosmic rays to produce radionuclides. Two of the most interesting and abundant of these are carbon 14 and tritium, which are also formed by the explosions of nuclear weapons. Other radionuclides formed by cosmic rays are beryllium 7, beryllium 10, sodium 22, silicon 32, iodine 129, and rhenium 187/osmium 187. The distribution of several of these cosmic-ray produced radionuclides in the sea can be used in studies of currents, mixing processes, and geochronology of the ocean.

Uses of naturally occurring radionuclides. The patterns of large-scale circulation and rates of water movement are often difficult to study. By correlating knowledge gained from studies of the distribution of various radioactive isotopes in the sea with knowledge obtained from classical oceanographic studies, however, it has been possible to improve our understanding of ocean circulation. The relatively new technique of using radioisotopes in this type of study makes it possible to evaluate classical models on the circulation of water in the oceans and to establish rates of movement of the water in models.

According to Broecker (Ref. 2), an isotope used in large-scale mixing studies should: (1) occur in measurable quantities in all parts of the ocean; (2) vary in concentration from one location to the next in amounts greater than the limits of measurement; (3) vary in mode and rate of introduction into the system as a known function of time and space; (4) act as an infinitely soluble salt, and thereby move with the water; and (5) have identifiable characteristics that make possible a separation into those amounts originating from natural and artificial sources.

Four naturally occurring radioisotopes—carbon 14, tritium, silicon 32, and radium 226—possess enough of the above mentioned characteristics to make them useful for circulation studies in the ocean. Of these, naturally occurring carbon 14, which has a half-life of 5600 years, has received the greatest attention. Carbon 14 reaches the ocean from the atmosphere in nearly constant amounts in both time and space. Carbon 14 measurements have a potential value in tracing water movements within oceanic reservoirs and particularly in the deep sea. The mechanism and the rate of production of tritium in the atmosphere are not understood as well as those for carbon 14.

Examination of material from the Discovery XVII satellite, which was exposed to intense solar flare radiation, has suggested that a significant fraction of tritium in the atmosphere is accreted from the sun. Because of its 12-year half-life, tritium is restricted to more rapid processes that occur in well mixed water. The application of silicon 32 to circulation studies is extremely difficult. Low levels of activity of this isotope make direct measurements in sea water time-consuming and expensive. Koczy (Ref. 5) has demonstrated that radium 226 can be used as a natural tracer. As mentioned previously, radium 226 is released from deep sea sediments into the water, and apparently this release is nearly constant with time and geographic location.

Artificially produced radionuclides. Fallout is the radioactive debris that settles to the surface of the earth after nuclear explosions. The amount and composition of fallout resulting from a specific explosion are determined by: (1) the height of the burst; (2) the size or power of the explosion; and (3) the composition of the fissionable material originally in the bomb. Since the oceans cover 71% of the earth's surface, it would be expected that about 71% of the worldwide fallout would fall into the oceans. Since about 61% of the northern hemisphere is covered by the oceans, approximately this percentage of the hemisphere's fallout would fall directly into the oceans. Also, some of the fallout on land is leached from the soil and carried by rivers to the ocean. Some of the artificial radionuclides that occur in the sea are shown in Table 2.

Although localized in distribution, another major source of artificial radioactivity is fuel processing and production plants, which discharge wastes into coastal waters or into rivers emptying into the sea. One such plant discharging radioactive effluent into the Irish Sea is the Windscale Works of the United Kingdom Atomic Energy Authority. This plant discharges about 90,000 curies of fission products per year. Over the past 10 years about 500,000 curies have been released (Ref. 6). Upon mixing with the receiving waters, radionuclides in the effluent from the Windscale plant may assume different chemical and physical states, but, in general, the distribution of radioactivity follows the known patterns of circulation and currents along the coast.

The Hanford Atomic Production Plant in the U.S. discharges radioactivity directly into the Columbia River. About 1000 curies per day of neutron-induced radionuclides are carried by the river to the Pacific Ocean 350 miles downstream (Ref. 11). Most of this radioactivity is due to radionuclides of relatively short half-lives, including neptunium 239 (half-life, 2.3 days), which has been detected at the mouth of the river. This radionuclide has little environmental significance, since it is not passed through the food chain and has such a short half-life (Ref. 4). Two other radionuclides, zinc 65 and chrom-

TABLE 2. ARTIFICIAL RADIONUCLIDES THAT HAVE BEEN IDENTIFIED IN THE SEA; CONCENTRATIONS HAVE VARIED WITH TIME AND SPACE DUE TO MAN'S ACTIVITIES

Nuclide and Daughter	Half-life
Fission Products	
Strontium 89	50.4 days
Strontium 90; yttrium 90	28 years; 64.4 hours
Yttrium 91	58 days
Zirconium 95; niobium 95	63.3 days; 35 days
Ruthenium 103; rhodium 103 m	41.0 days; 54 minutes
Ruthenium 106; rhodium 106	1.0 years; 30 seconds
Tellurium 129 m; tellurium 129	33 days; 74 minutes
iodine 129	1.6 × 10^7 years
Cesium 137; barium 137 m	30 years; 2.6 minutes
Cerium 141	32.5 days
Cerium 144; praseodymium 144	290 days; 17.5 minutes
neodymium 144	2.0 × 10^{15} years
Promethium 147; samarium 147	2.5 years; 1.3 × 10^{11} years
Iodine 131	8.05 days
Barium 140	12.8 days
Induced Nuclides	
Phosphorus 32	14.3 days
Sulfur 35	87.1 days
Chromium 51	27.8 days
Manganese 54	300 days
Iron 55	2.94 years
Iron 59	45.1 days
Cobalt 57	270 days
Cobalt 58	72 days
Cobalt 60	5.27 years
Zinc 65	245 days
Cadmium 113 m	14 years

ium 51, with longer half-lives, however, are of concern; both enter the Pacific Ocean and are present in detectable amounts in pelagic organisms some distance offshore. Zinc 65 is found generally in most marine organisms in the Columbia River estuary, and chromium 51 is concentrated in the lower trophic levels (Ref. 9).

It is more difficult to evaluate and control the release of radioactive wastes into the marine environment from mobile reactors, such as those in ships and submarines, than from land-based reactors. The geographical locations of these are selected with some consideration to the safety of man and his environment, and the radioactive wastes are released into a relatively restricted area. Ships and submarines, however, frequent ports and harbors where much damage would result if an accident should occur, and the wastes are dispersed over large areas of the open oceans where the possibility of danger to man and marine organisms is greatly reduced. The wastes from these mobile reactors usually consist of approximately 10 curies for each start-up and about 400 curies for a 50-day operation. These wastes become associated with the ion-exchange resins in the circuits. The radionuclides in these wastes are predominantly neutron-induced, rather than fission products. Radionuclides that may be present in the waste from nuclear-powered ship reactors are chromium 51, iron 55 and 59, cobalt 60, copper 64, zinc 65, strontium 90, zirconium 95, niobium 95, ruthenium 106, iodine 131, cesium 137, cerium 144, and tantalum 182.

Radioactivity released into the marine environment is a potential hazard to man, because he can be exposed internally by eating seafoods containing radioactivity (Table 3) and exposed externally to radioactivity that accumulates on the shore, fishing gear, and other objects that have been immersed in the water. The amount of radioactive material accumulated by seafood organisms in the vicinity of nuclear reactors is monitored to ensure the maintenance of safe levels of radioactivity. For example, the amount of radioactivity that has been disposed of at Windscale has been limited to a certain extent by the amount of radioactivity accumulated by ***Porphyra*** (Ref. 7), a seaweed used to make a delicacy known as laverbread. In instances such as this, the potential danger is determined by the amount of radioactivity accumulated by the seafood organisms and the quantity of the seafood eaten by an individual. Thus, an organism that concentrates less radioactivity, but is eaten in much larger quantity can be more dangerous than one that accumulates much more radioactivity, but is eaten in smaller quantities. Extensive monitoring of radioactive waste from Windscale during the past ten years, however, has shown no systematic increase in the levels of radioactivity in the environment (Ref. 6).

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TABLE 3. ESTIMATION OF ACCUMULATION IN EDIBLE PORTIONS OF SEAFOOD ORGANISMS OF SOME IMPORTANT RADIOACTIVE NUCLIDES RELATIVE TO THE CONCENTRATION IN SEAWATER[a]

Isotope	Edible Red Algae	Mollusks	Crustaceans	Fish
Fission products				
Strontium 90	10^{-1}–1	10^{-1}–1	10^{-1}–1	10^{-1}–1
Cesium 137	1 –10	10 –10^{2}	10 –10^{2}	10 –10^{2}
Cerium 144	10^{2}	10^{2}	10^{2}	10 –10^{2}
Zirconium 95	10^{2}–10^{3}	10 –10^{2}	10^{2}	1 –10
Niobium 95	10^{2}–10^{3}	10^{2}	10^{2}	1 –10
Ruthenium 106	10^{3}	1 –10^{3}	1 –10^{3}	1 –10
Induced activities				
Zinc 65	10^{2}	10^{3}–10^{5}	10 –10^{4}	10^{3}–10^{4}
Iron 55	10^{3}–10^{4}	10^{2}–10^{4}	10^{2}–10^{4}	10^{2}–10^{4}
Cobalt 60	10^{2}	10 –10^{3}	10 –10^{3}	10 –10^{2}
Manganese 54	10^{3}	10^{3}–10^{4}	10^{2}–10^{4}	10^{2}–10^{3}
Chromium 51	10 –10^{3}	10^{3}	10^{3}	10^{2}–10^{3}

[a] From Chipman (Ref. 3).

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REGULARITIES OF UPTAKE AND ACCUMULATION OF RADIONUCLIDES IN AQUATIC ORGANISMS

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EXPEDIENCY of aquatic radioecology creation is due to specificity of the aquatic environment and the important place occupied by aquatic organisms in the biosphere. It goes without saying there are general laws of uptake, accumulation, distribution and exchange of radionuclides by aquatic and land organisms. However, significant heterogeneity of environment and extreme variability of ecological factors modify and complicate their display on the land. Therefore, according to our conviction, the clearing up of aquatic radioecology regularities is simultaneously elucidation (in the most general form) of basis of radioecological features, acting on the land. Two circumstances, at least, are logical grounds for such a conclusion, namely: (1) land organisms descended from aquatic ancestors; and (2) aquatic environment is characterized by great uniformity. A conclusion is also obvious that radioecology of marine organisms is a key to radioecology of freshwater organisms. Really, sea water is characterized by significant constancy of its composition in contrast to a variety in chemical composition of different freshwater reservoirs conditioned by many reasons (composition of littering bed-rocks and inflowing waters, hydrological regime and intensity of aquatic life). This allows radioecological laws to be revealed in their most general form.

Unlike empirism, which is only trying to find differences everywhere, such an approach is very fruitful because it permits general regularities in various situations to be discovered. As is known, radioecology of aquatic organisms is the branch of science closely connected with nuclear sciences as well as biophysics, biochemistry, physiology, hydrobiology and biogeochemistry. Therefore, studying the subject—interrelations between radioactivity and hydrobionts—radioecology of aquatic organisms rests upon laws or regularities of adjacent fields of knowledge. At the same time, not seldom it has to take part in making up a deficiency of some important lacking regions among adjacent sciences, and hence radioecology makes its contribution to the development of these sciences. So, radioecology was faced with the fact of absence of biogeochemical information about many rare and dissipated elements, of which radionuclides are of great importance. Significant material, obtained by radioecologists on accumulation, distribution and migration of these radionuclides, enriched biogeochemistry by knowledge about behaviour of proper chemical elements in the biosphere. Undoubtedly, the intense interest of radioecologists in the missing links of biogoechemistry, as well as some other sciences, served like a stimulus for elaboration of unstudied fields.

Mechanisms of uptake and accumulation of radioactive substances by aquatic organisms may be considered from a biophysical as well as radioecological point of view. In the first case, main attention is paid to physico-chemical properties and processes in living structures which ensure permeability for substances from outside and inside environment (Troshin, 1956; Harris, 1960). In such investigations a circle of studying elements is not wide: potassium, sodium, calcium and a few other elements, ions and complexes. Radioecology, on the contrary, is interested, in the first instance,

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in the fate of all radionuclides and radioelements, interacting with living organisms, that is processes of their uptake and accumulation not only and not so much by the simplest or isolated living systems (erythrocytes, skin a.s.o.), but the whole organisms and their biocoenosis by means of isotopic exchange with solution, surface adsorption and through food chains. In this respect the following essential questions, connected with radioecological aspects of mechanisms of uptake and accumulation, are solved, namely: (1) characteristics of radioecological situation in environment and its change in time; (2) how, why, up to what degree and during what time accumulation of radionuclides takes place by separate species of aquatic organisms and biocoenosis; (3) what influence of physico-chemical state and chemical form of a radionuclide and its isotopic and nonisotopic carriers, are ecological factors of the environment (temperature, light a.s.o.) upon processes of its uptake and accumulation; (4) what is the role of biological factors in migration and distribution of radionuclides and radioelements in separate waterbasins and in the hydrosphere as a whole.

Let us try to deal to some extent with the initial notions and fundamental elements of radioecology which are under present discussion.

INITIAL FUNDAMENTAL NOTIONS

Nowadays most investigators in experimental as well as field radioecology of aquatic organisms use a *concentration factor* as the initial notion, characterizing uptake and accumulation of radionuclides, being the ratio of concentrations of a radionuclide in an organism and aquatic environment. Its use, of course, does not compete with the utilization of other quantitative ways of expression of hydrobionts' concentrative ability in solving separate special questions. However, the concentration factor is the unique universal measure of accumulation of chemical elements and their radionuclides, that is, it has the simplest sense: how many more times an aquatic organism accumulates a radionuclide (in a unit of living weight) than its concentration in surrounding water (in the same unit of weight or volume).

We are not really able to use such an important notion as *specific activity* (ratio of radioisotope atoms to proper chemical element atoms) for most radionuclides because concentration and physico-chemical state of isotopic carrier are unknown in organisms and water.

Similarly, such an important notion as *discrimination factor*, or observed ratio (ratio of concentration factors of two relative radionuclides or their nonisotopic carriers) may be applied in a limited number of cases: mainly for strontium and cesium.

Almost all investigators express concentration factors on the basis of living (wet) weight. It has all advantages over expressing concentration factors on the basis of dry weight, ash a.s.o., since we are able to estimate the role of living organisms in accumulation of radionuclides and radiation doses obtained by living tissues and cells. In some special cases it is worth while to calculate concentration factors also on the basis of dried or ashed weight.

The acceptance of the notion of concentration factor (on the living weight basis) by all aquatic radioecologists will be undoubtedly of benefit because it gives a possibility to compare directly the results of different authors.

On the basis of concentration factors were deduced various ratios (Polikarpov and Zesenko, 1965), with the help of which we can go on from some parameters, related with accumulation, to others by means of calculations. Their utilization ought to diminish the labour-consuming character of radioecological investigations. However, these ratios may be applied with confidence now only in marine radioecology in connection with great stability of chemical composition of aquatic environment in seas and oceans.

Uptake is the process of the entry of radionuclides in organisms and *accumulation* is its result. It is necessary to mention that we do not observe the real picture of *intake*, since the process of *loss* is accomplished simultaneously. Therefore uptake (and accumulation) is the difference between intake and loss. The process of loss can be studied directly.

Isotopic exchange is the exchange of radionuclide atoms (ions or complexes) with atoms (ions or complexes) of the same chemical elements (its stable isotopes) and conversely under the following conditions: the constant concentration of a chemical element in water occurring in the same physico-chemical state and chemical form with an added radionuclide. If the isotopic carrier is absent (or occurs in different state and form) or general concentration of the chemical element in water increases because of the addition of radionuclide (with isotopic carrier), uptake and accumulation will be determined by its concentration and by the presence of nonisotopic carriers. This process may be called *permeability* as distinguished from the process of isotopic exchange.

SOME BASIC RULES AND PRINCIPLES

Dependence of processes of uptake and accumulation on concentration of chemical elements

A number of investigators in different countries studied dependence of radionuclides' accumulation by freshwater and marine organisms on concentration of isotopic and nonisotopic carriers.

Timofeeff-Ressovsky (1957) and his school have particular merit in obtaining and summarizing the large material on this question. The rule, given below, is sufficiently substantiated experimentally as well as follows logically from the main radiochemical Khlopin law (Starik, 1960).

Rule 1. In the region of micro-concentrations (till 10^{-6}–10^{-4} moles/l.) under otherwise equal conditions the concentration of chemical element in a hydrobiont is directly proportional to such in water, that is, concentration factors are not dependent on concentrations (till mentioned limits).

Consequence 1. When adding a radionuclide having an isotope carrier, the concentration of the latter is not changed or changed in limits of microconcentrations, then the concentration factors of this radionuclide (and carrier) remain constant under otherwise equal conditions.

Consequence 2. If in the limits of microconcentrations the physico-chemical state and form of a chemical element (radionuclide) are changed, the concentration factors are also changed. Gileva (1965) showed, that at the yttrium concentration equal to 10^{-6} moles/l. hydroxide of yttrium is formed and its concentration factors by *Cladophora glomerata* decrease two times. Similar phenomenon, as she supposes, exists for promethium.

Consequence 3. In the region of macro-concentrations in water it is observed that nonisotopic carriers decrease concentration factors of a proper radionuclide by aquatic organisms. Therefore if concentration of nonisotopic carriers is a constant magnitude (in freshwater basins), the concentration factors of a radionuclide in a hydrobiont have no sense without information about concentrations of nonisotopic carriers in water.

Dependence of uptake and accumulation processes on physico-chemical state of radionuclide, pH, temperature and light

The physico-chemical state of different radionuclides (chemical elements) is little known. There are much less data on the importance of such a state for radionuclides uptake and accumulation in aquatic organisms. Nowadays, we can consider that strontium and cesium do not change their ion form, in which most of their atoms are present in the solution. Kečkeš *et al.* (1966) discovered that

^{106}Ru in the form of nitrate complex combination is accumulated by mussels 10 times less than it is done in chloride complex form. Trivalent chromic chloride is transformed to chromic hydroxide in sea water and the latter falls to the bottom, while hexavalent sodium chromate remains in the solution and is accumulated by sea worms (Chipman, 1966). Complex-forming substances are the mighty means of acting and studying the metal behaviour in aqueous solutions. EDTA sharply diminishes the concentration factor magnitudes of radionuclides of yttrium, cerium, zinc, cobalt, cadmium and iron; EDTA diminishes to a slight extent the concentration factors of zirconium, niobium, ruthenium, iodine, rubidium and calcium and increases the concentration factors of cesium and strontium in freshwater plants and animals. The first six elements have very high constants of stability of EDTA-complexes. Calcium is characterized with a more high stability constant than strontium. Therefore calcium concentration factors are diminished under the influence of EDTA and strontium (as an analogue of calcium) is accumulated in organisms. Change of concentration factors of the remaining radionuclides are connected, perhaps, with the sharp disturbance of calcium and hence general mechanism of mineral exchange (Timofeeva-Resovskaya, 1963).

There are very few data on the role of natural biocomplexions in the processes of radionuclides, accumulation by aquatic organisms. Jones (1960) supposes that the difference in ^{106}Ru accumulation by *Laminaria*, *Ulva* and *Porphyra* is based on different content of extractable alginic acid on their cell surfaces. It is possible that *Fucus* excretes into sea water some substances which prevent adsorption of ^{59}Fe (Taylor and Odum, 1960).

Data on the influence of pH of solution on accumulation of different radionuclides by aquatic organisms are yet not numerous and they are contradictory. Unlike the fresh waters (pH is changed in limits from 7·6 to 10), pH of sea water is a constant magnitude.

Materials on temperature and light action are few in aquatic radioecology. The characteristic temperature coefficient for some radionuclides is near 1 (for example, ^{144}Ce in brown algae). This may indicate adsorption processes. In relation to illumination, the chemical elements are divided into two groups: (a) indifferent to light, and (b) accumulating under light. However, there are not sufficient data to make any summary.

It is very interesting, for example, that ^{90}Sr is accumulated by killed brown algae (heating, boiling alcohol) as well as by living ones. Consequently, the process of its accumulation is based on sufficiently stable structures preserved for a relatively long time after death of the algae. When these seaweeds begin to disintegrate, then an opposite process of exit of ^{90}Sr into the surrounding water takes place. Thus, the mechanism of dividing similar elements (strontium and calcium) is connected not with the processes of vital activity but with rather more simple reactions in special structures. Studies of the mechanism of calcium and strontium discrimination in brown algae for the benefit of strontium may help to clear the mechanism of a complete division of strontium from calcium by Acantharia, building their skeleton only from sulphate strontium.

Kinetic features of radionuclides uptake and accumulation

Graphical material of different investigators, related to change of radionuclides accumulation by freshwater and marine organisms in time, shows in most cases that this process is represented as a straight line (logarithmic co-ordinates) till a constant level, namely stationary or equilibrium state. In special studies of this question, Barinov (1965) established that both uptake and loss processes are described not by exponential law (as is usually considered), but by more compound functions—logarithmic, power and power-logarithmic ones. In a general form this law can be explained by a wide set of separate elementary processes, obeying (each taken separately) the exponential law. This question is presented in detail in our report at this symposium (Polikarpov *et al.*, 1966). A similar phenomenon is described by the law of Way-Wigner: the mixture of radionuclides formed after a nuclear explosion disintegrates according to the power law (while the quantity of each radionuclide decreases according to the exponential law). Exponential distribution of disintegration constants leads to the power law of radioactivity decrease of a compound radionuclide mixture.

Thus there is a basis to form the following rule.

Rule 2. Kinetics of radionuclide uptake and loss by aquatic organisms are described not by exponential, but more compound laws (logarithmic, power, power-logarithmic functions). A study of kinetics of isotope exchange and energetical processes in its basis allows one to approach directly the investigation of nature and laws of uptake, accumulation and loss of radionuclides (chemical elements) by aquatic plants and animals.

Ways of entry of radionuclides into aquatic animals

Aquatic plants extract chemical elements and their radionuclides from water. In what main ways do aquatic animals receive them?

It was very tempting by purely formal analogy with land animals to explain intake of radioactive substances into aquatic animal organisms with food. But already first investigations showed that aquatic animals became radioactive in a short period of time without any feeding. Then radioecologists are divided into supporters and opponents of the food factor as the main source (in comparison with direct uptake from surrounding water) of radioactive substances for aquatic animals.

In favour of the supporters it is indicative of "obviousness" (bright schemes of food chains) and experiments with very dense suspensions of algae as a food for invertebrates, or to some extent with feeding of freshwater fish by food mass, in which ^{90}Sr was added. In favour of the opponents is the coincidence of concentration factors of radioactive as well as stable nuclides under hungry keeping of aquatic animals in radioactive solutions and in natural conditions, and also experiments with feeding of freshwater fish by living radioactive larvae of insects.

According to the work by Ophel and Judd (1966) ^{90}Sr contribution in the organisms *Carassius auratus* from water and food becomes equal when the strontium concentration factor of food material is about 100 units. It is necessary to underline that strontium concentration factors of marine food invertebrates and fish are much less than 100. Many freshwater animals being a food for fish also differ by their small concentration factors. For example, larvae *Chironomidae* have a ^{90}Sr concentration factor equal to 9 (Templeton, 1959).

Obviously, on the other side, animals obtain through food, some rich in energy substances, organic compounds which are necessary for processes of their vital activity. In other words the following picture becomes clear.

Tentative generalization 1. In a wide range of concentration factors (till 100 units) and usual biomasses of food organisms, water is the main source of most radionuclides (chemical elements) for aquatic, especially, marine organisms. Exclusions are carbon in the form of compound substances, organic phosphorus and perhaps a few other chemical elements, included in the composition of biologically active compounds.

This tentative generalization was made with a purpose to attract attention to the aforestated important but not sufficiently studied question.

All the foregoing is concerned with primary, constant inhabitants of aquatic environment. Cetacean and sea birds in the ocean, shore mammals and birds of freshwater basins, obviously ought to be studied, taking into account that their bodies are impermeable and that all chemical substances with food and water enter through the gastro-intestinal tract. However, it is difficult in this case to foresee *a priori*, which contribution will be more—from radioactive water or radioactive food.

It goes without saying that when there are no radionuclides in aquatic environment but organisms are radioactive, the food chains become the single way of uptake and subsequent migration of radioactive substances.

5. *Uptake and accumulation of radionuclides in biogeographical and bioceonological aspects*

On the basis of generalization of all published materials on concentration factors of different radionuclides in closely related species, inhabiting very different seas and oceans, we came to the following conclusion (Polikarpov *et al.*, 1966).

Rule 3. Concentration factors (in equilibrium state) of each separate radionuclide by closely related species of marine plants and animals (in limits of one genus or one family) do not differ significantly from each other in different seas and oceans with different salinity (from 35‰ to 17‰).

This rule makes it more easy to use the proper data, obtained in different ecological and geographical conditions, as well as their extrapolation on other, not yet directly studied, regions of the world ocean.

I should like also to attract attention to comparisons of concentration factors, obtained by the same method for some far relative marine and freshwater organisms (Polikarpov, 1961). It was ascertained that magnitudes of ^{137}Cs, ^{90}Sr and ^{35}S concentration factors in marine hydrobionts were, as it might be expected (because of macroquantities of carriers), about 10 times less than in the adequate freshwater organisms. Concentration factors of radioyttrium and radiocerium in relative marine and freshwater organisms were found to be close to each other, apparently in regard to micro-concentrations of isotopic carriers.

Tentative generalization 2. Concentration factors of radionuclides carriers which are present in water in microquantities are similar for relative marine and freshwater organisms.

Let us consider general questions of distribution between aquatic biocoenosis and aquatic environment (Polikarpov, 1964).

Rule 4. In the wide range of biomasses (up to 100 g m^3) and concentration factor magnitudes (to 1000) living organisms contain an insignificant part of radionuclides (chemical elements) presented in water. Otherwise, sea water would be transformed into distilled water. A similar situation we observe in bogs, the water of which really contains extremely few salts because of a relatively large part of plants and organic residues.

It is possible to point at the situations in seas when a large part of radionuclides in environment falls on living beings. This is first of all hyponeustonic (by determination of Zaitsev) biocoenosis of *Sargassum* algae, near bottom sea-weeds, biocoenosis of *Phyllophora* near seashore thickets of *Fucus*. In the layer or volume of habitat, in dependence on the properties of a biocoenosis, in enumerated cases great biomasses reach an average of several kilograms per cubic metre. Dominating species of these biocoenosis, which are also characterized by high concentration factors of many radionuclides, may be called not only bioindicators of radioactive substances, but also their bioconcentrators.

It stands to reason that the picture of radionuclides (chemical elements) distribution between biocoenosis and aquatic environment at some moment of time, does not reflect the radioecological (biogeochemical) mechanisms of migration of radioactive substances in the hydrosphere, main elements of which are reproduction and death of mass organisms, that is the circulation of living matter.

Temporary inhabitants of near-surface level—hyponeuston, described by Zaitsev (1961) may play a significant role in the conditions of shallow waters (up to 100 m depth). As a result of continuous migrations from the bottom (benthos) to the surface and back, these organisms can act like a pump which slowly but uninterruptedly pumps over radioactive substances from one level (or part) of the waterbasin to the other one.

At last, investigations of radioecological factor of artificial origin carried out in different seas and freshwater reservoirs established gradual increase of concentration and general amounts of ^{90}Sr and ^{137}Cs until recently in aquatic environment as well as in hydrobionts, and Parchevsky has found mathematical regularity describing the change of ^{90}Sr concentration in marine organisms during several recent years (Agnedal, 1966; Polikarpov *et al.*, 1966; Salo and Voipio, 1966; Schreiber, 1966).

Thus, it is possible to state that, *first*, aquatic radioecology does not only lean upon biophysical mechanisms of entry of chemical elements (radionuclides) into cells and tissues, but also starts to elaborate more compound, radioecological mechanisms of interaction between organisms and their biocoenosis with radioactivity of the environment; *second*, radioecology of aquatic organisms passes to the stage of generalizations and search of general laws; *third*, aquatic radioecology becomes one of the important fields of international scientific collaboration, the evidence of the development of which is the present International Symposium on radioecological concentration processes.

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Fallout Radionuclides in Northern Alaskan Ecosystems

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THE CONCENTRATION of radioactive fallout within various components of arctic ecosystems has been extensively studied during recent years as a consequence of the transmission in significant amounts of certain radionuclides to human populations. This results from (1) the dependence of northern native peoples upon wildlife resources for much of their physical and economic well-being; (2) the relatively simple food webs involved; and (3) the presence of several radionuclides from natural and artificial sources during the past decade, especially following the 1961-1963 series of atmospheric nuclear weapons tests conducted by Britain, France, Russia, and the United States. Several of these artificial radionuclides are of only transitory interest due to one or more of the following reasons: (1) their short physical half-life rapidly removes them from the environment, as in the case of iodine 131 (^{131}I); (2) they exist in trace amounts often measurable only by intricate radiochemical methods; or (3) they are "biologically inactive." Studies of these radionuclides in Alaskan arctic ecosystems have been previously reported.[1-3] Major research and radiological health emphasis has focused on the two long-lived fallout components, strontium 90 (^{90}Sr) and cesium 137 (^{137}Cs). Long physical half-lives of 28 and 30 years, respectively, and other properties make them available over extended periods of time and provide the opportunity to study cycling properties in biologic systems.

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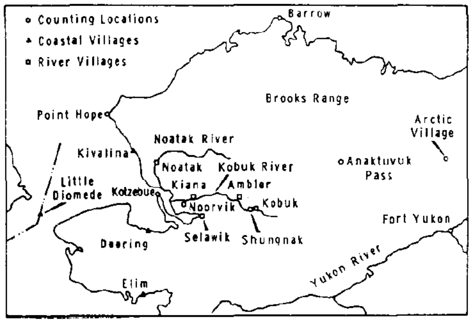
Much recent research has been devoted to the natural radiation environment of world populations, and notable in this category are the findings of significantly higher concentrations of lead 210 (^{210}Pb) and polonium 210 (^{210}Po) in northern ecosystems compared to temperate zone counterparts.[4-8] This condition has presumably existed for centuries and present data indicate that the deposition and transmission processes involved with these "natural fallout" radionuclides are much the same as those for ^{90}Sr and ^{137}Cs. The following discussion of our research into the routes, rates, and amounts of artificial fallout radionuclides in Alaskan arctic biota will therefore concentrate on ^{90}Sr and ^{137}Cs, with the implication that the results may apply widely to trace materials in northern environments.

Fallout Deposition in the Arctic

Although fallout deposition at 60 to 70° North latitude is but one fourth to one half that of the temperate regions,[9,10] the lichen-caribou (reindeer)-man food chain consistently yields high concentrations of most fallout radionuclides in man. In the case of ^{137}Cs, usually considered the most important from the standpoint of radiological health, body burdens in arctic native populations are often 50 to 100 times greater than those of temperate region peoples. In brief, this phenomenon is due to (1) the extremely effective retention of ^{137}Cs in lichens, (2) the importance of lichens as basic winter food of caribou and reindeer, and (3) the dependence upon caribou and reindeer for food by many northern peoples. Differences in the metabolic behavior of ^{90}Sr and ^{137}Cs account for the greater importance of ^{137}Cs under circumstances of the arctic food web. Being concentrated primarily in muscle and other soft tissues, ^{137}Cs is efficiently moved from one animal to the next; ^{90}Sr tends to be blocked from transfer by its concentration within the skeletal bone. Radiological health implications of these radionuclides are discussed later.

Fig 1.—Map of northwestern Alaska showing locations of native villages and whole-body counting locations.



Fallout Radionuclides in Alaskan Native Populations

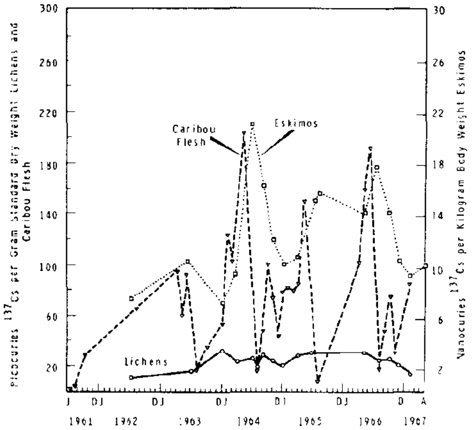
The degree to which the native populations of northern Alaska utilize caribou and reindeer for food varies considerably, de-

^{137}Cs Body Burden (nCi)*

	Summer 1962		Summer 1963		Summer 1964	
Location	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$
Anaktuvuk Pass	39	450	44	640	40	1,330
Kotzebue	112	150	102	120	114	340
River villages	35	150	16	150	26	360
Barrow	248	55	119	65	—	—
Point Hope	80	19	78	40	—	—
Coastal villages	8	100	—	—	2	130
Little Diomede	15	29	—	—	—	—
Fort Yukon	—	—	56	37	—	—
Arctic Village	—	—	—	—	25	640

* n = number of people; $\bar{x}$ = mean.

Fig 2.—Cesium 137 concentrations in lichens, caribou, and Eskimos at Anaktuvuk Pass, Alaska, during 1962 to 1967.



pending upon location and ethnological grouping. In the years 1962 to 1964 we measured γ-emitting radionuclide concentrations in 2,500 natives from the major ethnic groups of northern Alaska (Fig 1), and in extensive samplings of their foods.[11,12] Cesium 137 was the most important, and often the only γ-emitting fallout radionuclide found in the people, although several others were present in their foods. Average ^{137}Cs body burdens of adult natives of the various groups maintained the same general ranking during the study period (Table); the values were directly proportional to quantity of caribou or reindeer consumed as estimated by the people at the time of measurement. Maximum ^{137}Cs levels occurred in the Anaktuvuk Pass Eskimos, who are more dependent upon caribou for basic food than are the inhabitants of other Alaskan villages; median values occurred in river village and coastal Eskimos and the Arctic Village Indians, whose diets contain appreciable amounts of fish, marine mammals, or processed food; and lowest levels were found in Little Diomede Eskimos and Fort Yukon Indians.

Based on these data, our radiation ecology studies since January 1964 have centered at Anaktuvuk Pass (68° 10′ North, 151° 46′ West). The close relationship between the nunamiut Eskimos and their environment is exemplified by the cycling of ^{137}Cs in the lichen-caribou-Eskimo food web (Fig 2). The long-term trend was one of gradually increasing ^{137}Cs concentrations in all components of the food web until mid 1966. This is particularly apparent in the lichen data. Cesium 137 concentrations in caribou flesh followed a similar trend but with marked seasonal fluctuations and exceptionally high values during the spring of 1964 and the spring of 1966. The Eskimo ^{137}Cs body burdens closely followed the trends in caribou flesh, with an evident time-lag.

^{137}Cs in Alaskan Lichens

It is now apparent that lichens represent the most important reservoir of ^{137}Cs and other fallout radionuclides potentially available to man via food chains. Direct sorption of material (deposited mainly by precipitation) is the most significant process by which fallout is accumulated by arctic flora; plants with persistent aerial parts consistently contain greater amounts of fallout radionuclides than do those that produce new foliage each year.[13-15] Lichens serve as efficient concentrators of deposited fallout because of their longevity (decades or centuries), persistence of aerial parts, and their dependence upon nutrients dissolved in precipitation. These properties result in a tenacious holding of ^{137}Cs and maintain an appreciable level of the radionuclide in the principal winter diet of caribou and reindeer.

We have noted differences in ^{137}Cs concentrations between several lichen species representing various phenological types, which emphasize that radionuclide burdens in lichens tend to be ranked by each species' ecological niche, structural diversity, and growth pattern. Highest levels were usually observed in *Cornicularia* lichens on windswept ridges which were thus exposed to the atmosphere during periods of five to six months when snow shielded most of the other lichen species from direct fallout deposition. *Cladonia* lichens from snow accumulation areas tended to decrease in ^{137}Cs concentrations during periods of snow cover and then regain original levels following snow melt. Comparison of seasonal behavior of several other fallout radionuclides suggested that ^{137}Cs may be preferentially absorbed from the snow melt water.[16] The lichen curve in Fig 2 is thus expected to turn upward during the summer of 1967 as ^{137}Cs is released from melting snows.

The effective half-time of ^{137}Cs in lichens, as a result of biological and physical loss, has been estimated at 17 years[17] and six to ten years,[18] based on the change in ^{137}Cs levels in lichens, compared to ^{137}Cs deposition, in northern Scandinavia. Our experiments with ^{134}Cs and ^{137}Cs applied to natural lichen communities in northern Alaska indicate that the effective half-time could well exceed ten years.[19] Certainly, significant levels of ^{137}Cs in the arctic lichen reservoir should persist for many years yet.

^{137}Cs in Alaskan Caribou

Cesium 137 concentrations in caribou flesh consumed by Anaktuvuk Pass Eskimos revealed an annual pattern consisting of (1) a fairly stable winter level, followed by (2) an abrupt increase following the spring kill of migrating animals, (3) a rapid decrease to the annual low succeeding the fall kill of southward migrating animals, and (4) an increase to the winter levels. The abrupt increase in the spring is believed due to an influx of caribou migrating from distant ranges where the animals had grazed for several months on plants that contained ^{137}Cs concentrations greater than those of the Anaktuvuk Pass region. This conclusion is based upon the absence of a similar increase in lichen samples and on limited observations of caribou migration patterns. The rapid decrease of ^{137}Cs levels in caribou flesh during summer months is consistent with the short biological half-time (approximately three weeks) observed in reindeer.[17,20,21] The half-time in Alaskan caribou may well be shorter than the value of 27 days calculated from the decrease in ^{137}Cs flesh concentrations from May to September because there was undoubtedly some intake of ^{137}Cs during this period.[17] The prompt increase during fall months coincides with the change from a summer diet of green plants low in ^{137}Cs to the winter diet, which is largely composed of lichens. The magnitude of change of ^{137}Cs in caribou flesh from spring high to fall low is about a factor of 10; the lower values in fall caribou flesh were about the same as those in lichens. On the average, a concentration factor of about 2 occurred between the first and second trophic levels of the food web.

We consider the ^{137}Cs levels in spring caribou flesh at Anaktuvuk Pass during 1964 and 1966 to be unusually high, perhaps due to the animals' having wintered on ^{137}Cs-rich ranges not previously grazed, and/or to greater-than-normal precipitation. During 1963 and 1965, several stations in northern interior Alaska reported precipitation totals substantially greater than average and the increased fallout deposition resulting therefrom would be reflected by the lichens. Most of the ^{137}Cs deposited on lichens is retained in the upper few centimeters of living material. Since this is also the portion normally taken by grazing caribou, a major ^{137}Cs deposition could thus be transferred to caribou in the winter following such an event. Our results show a steady increase of ^{137}Cs in lichens and caribou flesh until mid 1966, whereas the Scandinavian Lapland data apparently reached maximum values in 1965.[17,18] This difference may be due to the reindeer herding practices of Lapps, that permits the identification of specific groups, and which also may result in animals regrazing ranges where the ^{137}Cs-rich top parts of the lichens had been previously removed.[22]

It is difficult to secure satisfactory detail on radionuclide concentrations among the caribou herds and their ranges in northern Alaska because of the extensive area, diverse environments, and uncertain migratory movements. During 1963 and 1964, we sampled caribou, reindeer, and moose from various Alaskan locations extending from Saint Paul Island in the Pribilofs to the Canadian border.[23] Results indicated that there were no major differences in the radionuclide burdens of reindeer and caribou from the same location. There was a sixfold difference in ^{137}Cs concentrations sampled at about the same time. Radionuclide concentrations in tissues of caribou were tenfold higher than in moose collected from the same environment at the same time. This difference is due to the moose's habit of browsing willow, birch, and aspen, rather than feeding on lichens. This also accounts for the lack of seasonal variation in ^{137}Cs concentrations in the moose. Caribou samples from the Arctic Slope of the Brooks Range and from the Arctic coast between Point Hope and Barrow tended to have lower ^{137}Cs concentrations than those from Anaktuvuk Pass. Animals from the Noatak and Kobuk River drainages tended to have the highest ^{137}Cs concentrations of the Arctic caribou herds. We have been unable to satisfactorily demonstrate a statistically significant difference between animals from various locations. Within any one herd of Alaskan caribou there has usually been a coefficient of variation of about 30% in the ^{137}Cs concentrations.[24] Scandinavian investigators report variability in reindeer ^{137}Cs values due to physiological factors.[18,20]

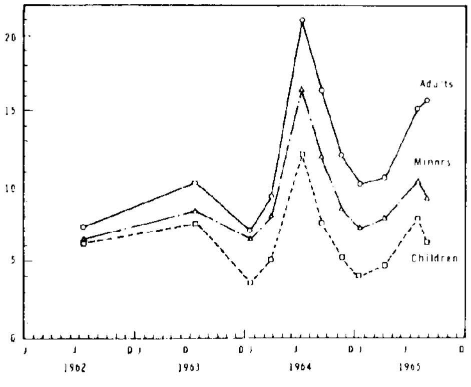
Comparison of limited numbers of samples from other areas suggests that the ^{137}Cs concentrations of the Alaskan Peninsula caribou herd were slightly greater than those of the Nelchina herd, which, in turn, were greater than those of the Arctic herd sampled at Anaktuvuk Pass. These differences correlate with the precipitation values for the respective areas; however, any such interpretation must be tempered by the previous discussion of variability. It should also be noted that the Peninsula and Nelchina herds are less important to native populations than is the Arctic herd.

^{137}Cs in Alaskan Natives

The relationship of the ^{137}Cs seasonal cycles in lichens and caribou to those in Eskimos at Anaktuvuk Pass reflects the dependence of these people upon their local environment. These people represent the last major remnant of nunamiut Eskimos who were formerly nomadic but now remain at their mountain village site. Their culture has always centered on the caribou, and the welfare of the people is still highly dependent upon the local environment. Caribou meat forms about one half of the total diet, partly because of necessity and partly because the people prefer it to other foods.

The seasonal pattern of ^{137}Cs concentrations in the Anaktuvuk Pass Eskimos lags behind the concentration in the caribou because of the timing of the main caribou kills and the stockpiling practices. Animals killed during the fall season (September-October) are returning from summer ranges and contain ^{137}Cs levels about one tenth those of spring-killed animals. This meat forms the base of the fall and early winter diet of the Eskimos. It is a preferred food because of its high fat content. Eskimo ^{137}Cs body burdens begin the September-January decrease when these animals are being eaten. During mid-winter the meat from caribou killed in the fall is usually exhausted and the Eskimos eat caribou obtained from nearby winter ranges, where lichens constitute the major food for the animals. This causes Eskimos ^{137}Cs body burdens to increase at a moderate rate during this period.

Fig 3.—Seasonal variation of ^{137}Cs concentration in adults (over 21 years), minors (15 to 20 years), and children (3 to 14 years) at Anaktuvuk Pass, Alaska.



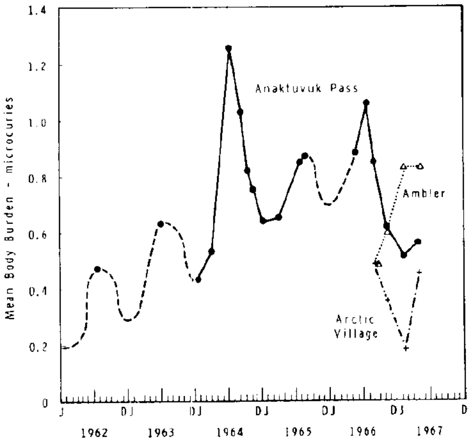


Fig 4.—Cesium 137 body burdens in adult natives at Anaktuvuk Pass, Ambler, and Arctic Village.

The spring caribou harvest is made during April and May as the animals migrate northward from their winter ranges, at which time they contain the highest ^{137}Cs concentrations of their annual cycle. This meat is stored in underground caches for use throughout the summer. Maximum observed Eskimo ^{137}Cs body burdens usually have occurred about two to three months after the dietary change to spring-killed caribou. The graph of Eskimo body burdens in Fig 2 prior to January 1964 and during the period August 1965 to May 1966 is drawn point-to-point and does not show seasonal variations as defined by bimonthly measurements made during the period January 1964 to August 1965 and from May 1966 to date. Comparison of ^{137}Cs body burdens from one summer to the next showed a pronounced increase of about 50% from 1962 to 1963, a doubling between 1963 and 1964, a 30% decrease from 1964 to 1965 and then a 25% increase from 1965 to 1966. This is consistent with the pattern of change of ^{137}Cs concentration in caribou flesh. However, the ^{137}Cs concentration in lichens showed a steady increase during this entire period. Thus, the decrease from 1964 to 1965 was inconsistent with the ^{137}Cs increases in lichens as were the abrupt increases during the spring of 1964 and that of 1966, which emphasizes the probable importance of caribou migration patterns in the determination of ^{137}Cs levels in the Eskimos.

Utilization of other animals for food had an insignificant effect upon the ^{137}Cs body burdens of the Anaktuvuk Pass residents. Dall sheep (*Ovis dalli*) are occasionally eaten for a short time in the autumn, principally by men trapping at distant locations from the village. Several samples of sheep taken by the hunters during the fall and winter months contained one seventh the ^{137}Cs concentrations of caribou ranging in the same general area. Ground squirrels (*Citellus parryi*) and arctic graying (*Thymallus arcticus*) are eaten in small amounts during spring and autumn months, respectively, and contain minute amounts of radionuclides. Moose (*Alces alces*) and barren-ground grizzly bears (*Ursus arctos*) are infrequently taken by hunters and also contain low ^{137}Cs concentrations.

Male adults between the ages of 21 and 50 usually have contained the highest body burdens of ^{137}Cs, apparently due to their greater proportion of muscle and greater consumption of caribou. Minors (15 to 20 years old) had 70% levels and children (3 to 14 years old) had levels of 50% as much ^{137}Cs per kilogram body weight as adults (Fig 3). Comparison of males and females during annual maxima indicated no important differences in their ^{137}Cs body burdens until about the age of 20; males then consistently contained more ^{137}Cs than did females. Maximum differences between sexes occurred at about the age of 40 years, and the difference then decreased during advanced ages.[25] Maximum body burdens were usually twice the mean of all adults and were usually found in the same few men.

The rate of elimination of ^{137}Cs from the body was found to vary with age and body weight in a study of 28 Anaktuvuk Pass natives who were removed from their normal caribou meat diet during August 1965.[19] Retention half-times were about 65 days for adults, 52 days for minors, and 40 days for children. These values are comparable to those reported for other arctic peoples, and account for the prompt human response to any change in the ^{137}Cs level in their diet.

The differences in food-gathering cultures of northern Alaska, result in important seasonal changes in ^{137}Cs in the native diet. We are currently defining and comparing the seasonal cycles of different caribou utilization patterns at three Alaskan villages: Anaktuvuk Pass, Arctic Village and Ambler. Anaktuvuk Pass has already been discussed in detail. Ambler was selected for study because it is near the center of habitation of the river village Eskimos along the Noatak and Kobuk rivers. These people depend upon caribou for about 30% of their food, particularly during fall and winter months when caribou are nearby. Fish comprises about 25% of their diet and marine mammals contribute about 11% during spring months. Arctic Village is a northernly Athapaskan Indian village in the Alaskan interior whose residents depend upon caribou for about 40% of their food. Heaviest utilization occurs during fall, winter, and spring when the caribou migrate past the village.

Periodic measurements of native ^{137}Cs body burdens at the three villages were begun in October 1966 and four visits have now been made. Results (Fig 4) show that the seasonal cycles of ^{137}Cs in the people at Anaktuvuk Pass and Ambler are distinctly different with the Ambler high occurring during the Anaktuvuk low and vice versa. Arctic Village suffered a disastrous loss of the entire fall kill of caribou meat due to unseasonably warm weather during September and October 1966 and experienced hardship during the following winter. Fish and a few moose provided their main wild meat for most of this period, and ^{137}Cs burdens decreased by 60% in about four months. A three- to four-week supply of caribou was obtained in March and ^{137}Cs body burdens returned to October levels in the five weeks between the arrival of this meat and the last measurement. The recent record of ^{137}Cs levels for this village is, therefore, atypical.

Wolf flesh obtained from the Anaktuvuk Pass region, where wolves are presumably dependent upon caribou for their main diet during the period of September to March, contained about twice the ^{137}Cs concentrations found in caribou flesh. Estimates of Eskimo ^{137}Cs concentrations in flesh, based on conversion of body burden to muscle mass equivalent, yielded values for human flesh about the same as those for caribou flesh. About half the Eskimos' food was caribou meat, and it is therefore reasonable to assign a concentration factor of 2 to the caribou-carnivore (including man) link of the Alaskan food chain.

^{137}Cs-^{90}Sr Relationships in Biota

Strontium 90 is more mobile within lichens than is ^{137}Cs, as indicated by (1) a change in the $^{137}Cs/^{90}Sr$ ratio from about 1.4 to 2.0 in atmospheric fallout to about 3 to 5 in most lichen samples; (2) a fairly uniform ^{90}Sr distribution throughout natural lichen thalli compared to greater ^{137}Cs concentrations in the upper portions of lichens than in the lower portions; (3) recent labeling experiments reported by Russian investigators[21]; and (4) our experiments with radionuclides applied to natural lichen communities in northern Alaska.[19] This mobility accounts for the diminution of ^{90}Sr concentrations in Alaskan lichens since January 1964, compared to the steady state of ^{137}Cs concentrations (Fig 5). Strontium 90 concentrations in caribou bone samples increased steadily during the period 1962 to 1965 and then leveled off during 1966. Most of the animals were 4 to 9 years old, which may account for the time-lag between the trends in animals and in their principal source of ^{90}Sr. Comparison of levels in a few caribou bone samples as related to the animals' age disclosed no clear relationships; however, this may well be due to small sample size variability. Schultz and Flyger[26] reported a statistically significant difference between ^{90}Sr concentrations in various age classes of Maryland deer mandibles and an increasing trend during a period of increasing fallout deposition.

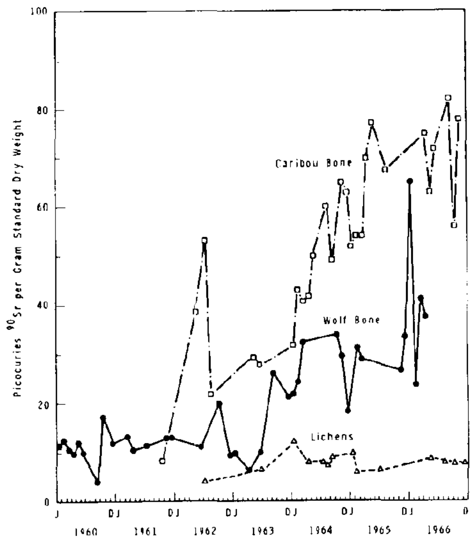


Fig 5.—Strontium 90 concentrations in biota at Anaktuvuk Pass, Alaska, during 1960 to 1966.

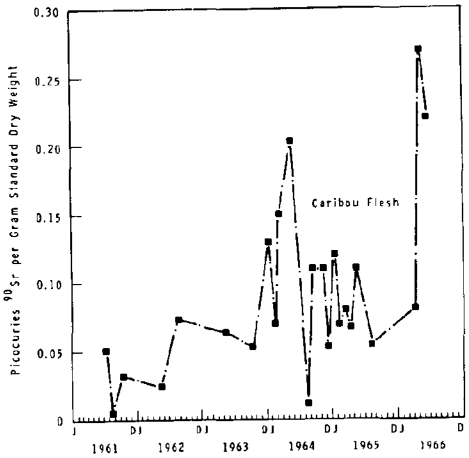


Fig 6.—Strontium 90 concentrations in caribou flesh at Anaktuvuk Pass, Alaska, during 1961 to 1966.

Strontium 90 concentrations in bones of about 15 wolves taken near Anaktuvuk Pass each year, mostly during winter months, of the period 1960 to 1966, showed an increasing trend with time. Amounts seemed fairly stable at about 10 pCi/gm during 1960 to 1963 and then increased and averaged about 30 pCi/gm during 1964 to 1966. (Radiologic units commonly used to describe small amounts of radionuclides are expressed as fractions of the standard curie [Ci] which is a unit quantity of any nuclide in which 3.7×10^{10} disintegrations occur per second. A picocurie [pCi] is 10^{-12} curie, a nanocurie [nCi] is 10^{-9} curie, a microcurie [μCi] is 10^{-6}

curie, and a millicurie [mCi] is 10^{-3} curie.) These values were about one half those in caribou bone and illustrated the blocking of transfer from herbivore to carnivore because of ^{90}Sr concentration in bone. Such transfer as did occur may be explained by the fact that wolves eat appreciable amounts of caribou bone.[27] The trend of ^{90}Sr concentration in wolf bones was more closely allied to that in caribou bone than with the trend in caribou flesh (Fig 6). The flesh values fluctuated substantially about a median value of approximately 0.07 pCi/g, or about 1/500 the concentration in caribou bone. Maximum ^{90}Sr concentrations in caribou flesh occurred during May in 1964 and 1966, and minimum values prevailed during August; these corresponded to times of maximal and minimal ^{137}Cs concentrations.

Radiological Health Considerations

The radiological health implications of current amounts of ^{90}Sr and ^{137}Cs in Alaskan biota are logically considered separately.

Strontium 90 in humans cannot presently be quantitated by whole-body counting, and the most direct method of evaluating human radiation exposure is by calculating the ^{90}Sr intake in foods and comparing it with standards adopted by national and international agencies. Estimates of ^{90}Sr ingestion via caribou meat by Anaktuvuk Pass adult Eskimos during summers of 1961 to 1966 were 11, 5, 13, 24, 15, and 31 pCi/day, respectively. This plane of ^{90}Sr was presumably maintained for about four to five months following the spring kill of caribou and it then decreased with the use of fall-killed animals. Thus, ^{90}Sr ingestion rates of these people were within Range I (0 to 20 pCi/day) of the Federal Radiation Council's Radiation Protection Guide,[28] except for brief periods during the summers of 1964 and 1966.

Whole-body radiation exposures of Anaktuvuk Pass adults were calculated by determining average annual ^{137}Cs body burdens from the area under the curves in Fig 4 and applying appropriate equations.[29,30] The annual exposures thus estimated were 56, 90, 144, 138, and 142 millirem (A millirem corresponds to an absorbed dose in tissue that is considered to result in biological damage equivalent to that produced by one millirad [0.001 rad] of x-radiation [of about 200 kv energy]. The rad corresponds to an energy absorption of ionizing radiation in the medium of 100 ergs/gm and the medium referred to here is human tissue. The millirem and millirad may be considered equivalent for the purposes of this discussion.) for the years 1962 to 1966. For purposes of comparison, the dose to which all people are exposed because of cosmic radiation, naturally-occurring radionuclides in rocks and soil, and naturally-occurring radioactive isotopes which are in our bodies, is about 130 millirads per year. The probability of significant biological effects from these levels of exposure is extremely remote.[31,32] While it is impossible to give positive assurance that there is *no effect* of fallout radiation upon human or animal populations of northern Alaska (or of any other area of the earth), it is the concensus of responsible scientists that current exposure levels are substantially below those at which biological effects have been observed, and the measures to mitigate these radiation exposures would be misdirected. Misinformed or irresponsible discussion of the Alaskan fallout situation in terms of potential hazard has in the past created serious concern among the native peoples most vitally involved. Further, any remedial measures yet suggested could be expected to have important deleterious effects on the well-being of the villagers.

Future Situation

Assuming no future increases in fallout deposition rates will occur, the amounts of radionuclides in northern Alaskan ecosystems should continue to decline. We can infer from estimates of a ten-year effective half-time of ^{137}Cs in lichens that it will remain the artificial radionuclide of major importance. Unusual situations, such as the exceptional ^{137}Cs concentration in caribou flesh at Anaktuvuk Pass during the springs of 1964 and 1966, can be expected to recur; however, the period of average build-up appears to have passed. The present trend of many Alaskan native groups towards more dependence upon processed food and other cultural innovations that result in less dependence upon caribou and reindeer for food will result in reduced radionuclide intake. The recent Chinese nuclear weapons test may reverse these trends, particularly if they portend further high energy yield tests in the atmosphere.

Summary

Studies of radioactive fallout in Alaskan arctic ecosystems were conducted during the period 1959 to 1967 to define routes, rates, and amounts of several radionuclides in a region where wildlife resources are important to human welfare. Emphasis was placed on seasonal measurements of ^{90}Sr and ^{137}Cs in all trophic levels of the lichen-herbivore-carnivore food web at Anaktuvuk Pass during the years 1962 to 1967.

Cesium 137 concentrations increased by a factor of two at each successive trophic level of the lichen-caribou, reindeer-man, wolf-food chain. This resulted from (1) the unusual capacity of lichens to absorb and retain fallout materials, especially ^{137}Cs; (2) the utilization of lichens as a basic winter food by caribou and reindeer; and (3) the dependence upon caribou and reindeer for food by northern peoples and wolves. Strontium 90 was less important than ^{137}Cs because it was more mobile in lichens and tended to be blocked from appreciable transfer to carnivores by accumulation in bone.

Regional and local differences in ^{137}Cs concentrations were noted among plant and animal species and among ethnic groups of natives. A definite seasonal cycle of ^{137}Cs was found in the biota which illustrated their close relationship to the environment and the simple structure of arctic ecosystems. Cesium 137 concentrations in caribou flesh and Eskimos at Anaktuvuk Pass attained maximum values during spring and summer months, respectively. Unusually high values during 1964 and 1966 were ascribed to caribou migrations from distant winter ranges with greater ^{137}Cs levels in lichens than those measured in lichens at Anaktuvuk Pass, and to the subsequent use of these animals by the Eskimos.

Radiation exposure of Anaktuvuk Pass Eskimos from ^{137}Cs body burdens during each year of the period 1962 to 1966 varied from 59 to 144 millirem, which is of the same order as natural background radiation. Except for brief periods, ^{90}Sr ingestion rates via caribou meat was within Range I of the Federal Radiation Council's radiation protection guides.

It is concluded that appreciable amounts of fallout radionuclides, especially ^{137}Cs, will remain in Alaskan biota for several years. The radiation exposure is not now, nor expected to be, hazardous to animals (including man). We believe continued study is necessary to continue to increase and improve knowledge of the processes involved in radionuclide transfer within Alaskan arctic ecosystems.

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Dr. Max C. Brewer, Director of the Arctic Research Laboratory, Barrow, Alaska, provided use of field facilities. The Alaska Department of Fish and Game supplied bones from 50 wolves for ^{90}Sr analysis. The Public Health Service Alaska Native Service Hospitals at Barrow and Kotzebue provided use of hospital facilities. Mrs. D. D. Wade and Mr. H. A. Sweany processed samples and data.

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MODELING THE BEHAVIOR OF RADIONUCLIDES IN SOME NATURAL SYSTEMS[1]

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Abstract. Some quantitative aspects of the uptake, retention, and food-chain cycling of radionuclides are assessed through simple models. Special emphasis is given to the unexpected observation that relative variability usually does *not* increase up the food chain, as might well be expected on the a priori basis that animals tend to function as "integrators" over their food sources. The influence of some relevant populational and physiological factors is briefly considered, and it is suggested that variability in loss and excretion rates may often be the major component in observed variances. Models for such circumstances are discussed, and the influence of body size on excretion is stressed.

Introduction

Our efforts here are largely concerned with the simplest uptake and retention model. Our immediate interest in models lies in their use in appraising the sizable variability observed in the radionuclide content of food chains. In this paper we are largely concerned with individuals and populations – mostly of animals – and not with connected compartments. We mostly ignore the auxiliary influences of temperature, nutrient limitations, mineral deficiencies, oxygen concentration, and similar factors.

The limitations thus imposed can be taken to either prohibit any success or, alternatively, to permit concentrating on major features and principal components of variability. We leave the reader to judge for himself, but note that we do not claim to do more here than make a beginning – one which we hope may be useful in future data collection and experimentation, and perhaps in stimulating rather more sophisticated efforts at model building.

Uptake and Retention Models

As was pointed out in the introduction, we have little more to offer than an introduction to some prospects for model building. We propose to consider only variations on the simple model commonly used in radionuclide studies. Five categories will be considered, based essentially on a categorization of kinetic models given by Turner, Monroe, and Homer (1963).

The basic model is a linear differential equation with constant coefficients:

$$dy/dt = \lambda - \mu y \ ,$$

with solution

$$y = \frac{\lambda}{\mu}[1 - e^{-\mu t}] + y_0 e^{-\mu t}$$

and asymptote

$$y_\infty = \frac{\lambda}{\mu},$$

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[1] This paper is based on work performed under United States Atomic Energy Commission Contract AT(45-1)-1830.

Eberhardt, L. L. and R. E. Nakatani. 1969. Modeling the behavior of radionuclides in some natural systems. pp. 740-750. In: Symposium on Radioecology. (D. J. Nelson and F. C. Evans, eds.). U.S. AEC report CONF-670503.

where

$y = y(t)$ = body burden at time t,

λ = intake per unit time,

μ = excretion rate, or "loss coefficient,"

y_0 = initial value of body burden (may be zero).

We are concerned here only with what might be called "process" models, i.e., those in which the variability arises in the actual working of the system considered. Consequently, we largely exclude from discussion the simplest method of incorporating a component of variation, which is to add on an "error term":

$$y = f(t) + \epsilon ,$$

where ϵ is usually considered normally distributed with mean zero. In the present situation, the statistician's labors are considerably lightened by considering the errors "multiplicative," that is:

$$y = f(t) \cdot \epsilon ,$$

since taking logarithms may yield a model which is "linear with additive errors," the usual case in present context being:

$$y = y_0 e^{-\mu t} \cdot \epsilon ,$$

$$\log_e y = \log_e y_0 - \mu t + \log \epsilon ;$$

hence, it is a great convenience to suppose ϵ approximately log-normally distributed.

I. *Linear Differential Equations with Coefficients as Functions of Time.* While such models do not incorporate a component of variability (except perhaps by the device just described), they are needed in various situations. The simple cases are, of course, those where λ is considered to vary in time. Some examples are:

(1) Continuously decreasing intake, as instanced by:

$$\lambda(t) = \lambda e^{-kt} \qquad (k < \mu) ,$$

with solution (initial conditions; $y = 0$ at $t = 0$):

$$y = \frac{\lambda}{\mu - k}(e^{-kt} - e^{-\mu t})$$

and maximum value:

$$y = \frac{\lambda}{\mu}\left(\frac{k}{\mu}\right)^{k/(\mu-k)} \quad \text{at } t = \frac{-\log_e(k/\mu)}{\mu - k} .$$

This is an equation widely used in analysis of Nevada Test Site radioiodine data (e.g., F. B. Turner 1963) and which might also be applicable to some of the ecological studies of radioiodine from world-wide fallout (e.g., Hanson *et al.* 1963, Whicker *et al.* 1966).

On some occasions, one may want to model an increasing intake (over a finite time span), so that

$$\lambda(t) = \lambda e^{kt} \text{ or } \lambda(t) = \lambda a^t .$$

We have found such a device necessary in attempting to appraise the late summer and fall increase in body burdens of ^{137}Cs in Alaskan caribou (Eberhardt, unpublished).

(2) Cyclic phenomena. Many sources of radionuclides in natural environments have strong daily or seasonal trends, as, for example, those induced in the Columbia River on a daily basis by a low-head power dam just upstream and the seasonal dilution due to spring "freshet" conditions. As yet, we have not attempted to model such effects, but offer the following simple relation as an illustration:

$$\lambda(t) = \lambda(1 + \sin t) ,$$

which has the equilibrium solution:

$$y = \frac{\lambda}{\mu} + \frac{\lambda(\mu \sin t - \cos t)}{1 + \mu^2},$$

suggesting that a long effective half-life (μ small) may "damp out" the time-related effect (term on the right ranges $\pm\lambda$), while shorter half-times might yield various oscillations out-of-phase with intakes.

II. *Non-Linear Differential Equations.* No attempt will be made to discuss non-linear situations in this paper.

III. *Differential Equations in Probability Functions (Stochastic Processes).* If the problem is considered in terms of the behavior of individual radioactive particles (atoms or molecules), there is a probabilistic analogue for the basic deterministic equation. Some details are given by Feller (1957: 414) who points out that the process either tends to a Poisson process as t becomes large, or follows the Poisson "law" exactly if no particles are in the system at $t = 0$.

The basic differential equations are:

$$P_0'(t) = -\lambda P_0(t) + \mu P_1(t) ,$$

$$P_n'(t) = -(\lambda + n\mu)P_n(t) + \lambda P_{n-1}(t) + (n + 1)\mu P_{n+1}(t) ,$$

with λ and μ now playing the part of transition probabilities.

The mean value is:

$$M(t) = \frac{\lambda}{\mu}(1 - e^{-\mu t}) + ie^{-\mu t} ,$$

where i is the initial condition. Thus, the average number of particles follows precisely the same course as that given by the deterministic model.

With the help of the probability generating-function (Feller, *ibid,* p. 435, No. 13) one can easily find the coefficient of variation for the process, and the following limits:

$$\lim_{i \to \infty} \text{C.V.} = 0 ,$$

$$\lim_{t \to \infty} \text{C.V.} = \frac{1}{\sqrt{\lambda/\mu}} ,$$

which only supplements the fairly obvious conclusion that the probabilistic process behaves almost exactly like the deterministic model when the number of particles is sufficiently large. Since the typical application deals with very large numbers of individual radioactive particles, it is evident that the probabilistic version of the standard differential equation fails to account for the variability ordinarily observed. Efforts to consider the individual "particles" as some aggregation of radioactive particles (e.g., a single meal) immediately run afoul of the definition of transition probabilities since such aggregates are soon broken up in assimilative processes.

Wiggins (1963, 1964) has derived another stochastic model, again on the basis of behavior of individual particles. While the process is similarly unsuitable for representing system variability, the mean value is of particular interest in regard to a model presented under category V below.

The basis for the model is that the probability of a particle leaving the system in the interval $(0,t)$ is taken to be

$$\rho(0,t) = \rho(t) = \frac{\alpha}{1+\beta t},$$

where α and β are constants.

Under conditions of independent behavior of particles and vanishingly small probabilities of simultaneous changes of state by two or more particles, the average number of particles retained in the system can be shown to be of the form:

$$E[X(t)] = \gamma(1+\beta t)^{-\alpha/\beta}.$$

Justification for the model depends, of course, on the assumption of a transition probability decreasing in time according to the rule specified above.

IV. *"Combination" Models.* The general characteristics of animal systems suggest that intakes ought to be regarded as a stochastic process, in that they usually come in discrete "packets" of variable radionuclide content (under other than laboratory conditions, at least). In terms of voidings, excretion might be similarly regarded. However, excretion from a metabolically active tissue (e.g., ^{137}Cs in muscle) or a storage area (possibly DDT in fat) seems rather more realistically modeled as a continuous process.

The accumulation process may then be represented by:

$$Y = X_1 e^{-\mu t_1} + X_2 e^{-\mu t_2} + \ldots + X_i e^{-\mu t_i} + \ldots + X_n e^{-\mu t_n},$$

where

Y = current body burden,

X_i = radionuclide content of i^{th} most recent intake,

t_i = time interval from present to i^{th} most recent intake,

μ = excretion coefficient (assumed constant).

It seems reasonable in many circumstances to assume the X_i randomly and independently selected from the same "population" following some statistical frequency distribution of radionuclide content. Under natural conditions, assuming independence of the t_i seems somewhat less satisfactory on the grounds that timing of any particular meal (and its size) may condition the length of interval to the next. There has, however, been a considerable recent interest in the subject (cf. Holling 1966, and references therein) so that reasonable sorts of assumptions about distribution of time intervals may soon become available. Given such a distribution, the problem becomes that of deriving the distribution of Y.

If the intakes occur at uniformly spaced intervals, so that (say) $t_i = i$, and $e^{-\mu} = a$, then

$$E(Y) = E(X)\frac{a}{1-a}(1-a^n) = E(X)\frac{e^{-\mu}}{1-e^{-\mu}}(1-e^{-\mu n})$$

$$\doteq \frac{E(X)}{\mu}(1-e^{-\mu n}) \text{ (for } \mu \text{ small)},$$

which is thus the analogue of the familiar differential-equation model.

Under somewhat less restrictive conditions, we may consider the mean and variance of Y conditional on the observed set of t_i. Writing

$$C_i = e^{-\mu t_i}$$

and utilizing the assumed independent selection of the X_i from a common frequency distribution, we find the mean and variance to be (by the well-known rule for linear combinations of independent random variables drawn from common distribution):

$$E(Y \mid t_1, \ldots, t_n) = E(X) \cdot \sum_{i=1}^{n} C_i \, ,$$

$$V(Y \mid t_1, \ldots, t_n) = V(X) \sum_{i=1}^{n} C_i^2 \, ,$$

and the squared coefficient of variation thus is:

$$[CV(Y)]^2 = \frac{V(X)}{[E(X)]^2} \frac{\sum_{i=1}^{n} C_i^2}{\left(\sum_{i=1}^{n} C_i \right)^2} ,$$

and quite clearly the coefficient of variation of Y is very much smaller than that of the X_i (since all the C_i, with the possible exception of C_1 are less than unity). For the case of uniformly spaced intervals, we easily find

$$[CV(Y)]^2 = [CV(X)]^2 \left(\frac{1 - e^{-\mu}}{1 + e^{-\mu}} \right) \left(\frac{1 + e^{-\mu n}}{1 - e^{-\mu n}} \right) ,$$

so that if the half-time is at all long (μ thus is small) and n moderately large (i.e., a considerable number of meals have been eaten), we have

$$[CV(Y)]^2 \doteq [CV(X)]^2 \cdot \frac{\mu}{2} ,$$

a very considerable reduction. Perhaps this is a somewhat elaborate description of an obvious proposition – that an animal tends to "average over its food supply." This is, however, a point that seems to be neglected on occasion in model building, and, much more importantly, to be refuted by the available data on radionuclide abundance in food chains. That is, several sets of data (described below) suggest that the coefficient of variation does not decline in a food chain, but tends rather to hold roughly constant. One is immediately led to suspect that the excretion coefficient (μ) may vary over a population of individuals, leading to the next category of models. Jacquez and Mather (1966) provide some further elaboration of material in the present section. Rustagi (1965) discusses a model with stochastic inputs and outputs. He assumes (p. 763) that the differences between inputs and outputs "are independent and identically distributed random variables," so the results presumably apply only under equilibrium conditions. The approach seems of considerable value for those studies where the only measurements possible are those of intake and excretion.

V. *Linear Differential Equations with Variable Coefficients.* Such models may conveniently be introduced by considering "half-time" determinations:

$$y = y_0 e^{-\mu t} .$$

Rearranging in the form often used to express retention as "proportion of initial burden":

$$y/y_0 = e^{-\mu t} ,$$

$$\log_e(y/y_0) = -\mu t .$$

Two kinds of experiment may be considered: (1) those where "whole-body counts" may be conducted, and estimates of μ made for individuals, and (2) those where a group of animals must be sacrificed periodically for assay (e.g,, for beta emitters or pesticides), either individually or as "pooled" samples.

Most of the difficulties pertain to the second kind of experiment, but an average excretion coefficient may readily be determined if individual animals are assayed, i.e.,

$$E[\log_e (y/y_0)] = -E(\mu)t \ ,$$

that is, geometric means are employed. When samples are pooled, and excretion coefficients differ among individuals, a plot of proportions retained against time on semi-logarithmic paper may yield a curve, even when only a "single component" of excretion is involved (there are, of course, often at least two distinct coefficients actually to be considered).

In order to derive a relationship representing this situation (but for single-component cases) we assume the excretion coefficient (μ) to follow a gamma distribution in the population of individuals:

$$f(\mu) = \frac{\beta^\alpha}{\Gamma(\alpha)} \mu^{\alpha-1} e^{-\beta\mu} ,$$

where α and β are constants, and

$$E(\mu) = \alpha/\beta \ , \qquad V(\mu) = \alpha/\beta^2 \ .$$

This is admittedly an arbitrary assumption, but realistic in the sense that the gamma distribution is quite flexible, ranging from highly skewed to nearly symmetrical, depending on values of α and β.

We now find the expectation of proportion retained:

$$E\left(\frac{y}{y_0}\,\middle|\, t\right) = E(e^{-\mu t}) = \frac{\beta^\alpha}{\Gamma(\alpha)} \int_0^\infty \mu^{\alpha-1} e^{-\mu(\beta+t)} \, d\mu$$

$$= \left(\frac{\beta}{\beta+t}\right)^\alpha = \left(1 + \frac{t}{\beta}\right)^{-\alpha} ,$$

so that plots of average proportion retained may be expected to be linear on a double-logarithmic plot, providing the proper "scale factor" (β) is used.

When β is "large" the relation above becomes indistinguishable from the usual exponential representation with $\mu = \alpha/\beta$.

One can see this either by expansion into series and term by term comparisons, or by taking limits:

$$\lim{}^* \left[1 + \frac{(\alpha/\beta)t}{\alpha}\right]^{-\alpha} = e^{-\mu t} \ .$$

The conditions thus imply that the distribution (gamma) of μ is concentrated at the mean, i.e.:

$$E(\mu) = \alpha/\beta \ ,$$

$$V(\mu) = \alpha/\beta^2 = \mu/\beta \to 0 \ .$$

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*Conditions on the limit are: $\alpha \to \infty$, $\beta \to \infty$ in such a manner that $\alpha/\beta = \mu$.

We have thus reached much the same formulation as that given by Wiggins (1963, 1964, see III above), but from an entirely different point of view. One model proposes that the probability of excretion changes in time, while the other postulates the rate to be constant for any given individual, but that averages over groups of individuals behave according to a "power law."

A more widely useful derivation should represent the entire uptake and retention process. A major uncertainty lies in the behavior of relationships between intake and excretion over populations of individuals. If we consider intake fixed (as in experiments using injections or force-feeding), the basic equation becomes:

$$E(y|\lambda,t) = E\left[\frac{\lambda}{\mu}(1 - e^{-\mu t})\right] = E\left(\frac{\lambda}{\mu}\right) - E\left(\frac{\lambda}{\mu} e^{-\mu t}\right) = \frac{\lambda\beta}{\alpha - 1}\left[1 - \left(1 + \frac{t}{\beta}\right)^{-(\alpha-1)}\right] ,$$

which is thus analogous to the simple deterministic equation.

Extension to the general situation where intake is not fixed might be undertaken through the relationships of food consumption and excretion rates to body size. That is, the general metabolic relation (Brody 1945):

$$X = AW^B ,$$

where

X = a given metabolic function,

W = body weight,

A, B = constants,

might be used to inter-relate λ and μ. We do not feel justified in pursuing the prospect much further here, but think it important to note that the coefficient B is always less than unity, making the standard practice of administering treatments or expressing results on a per-unit-weight basis an inadequate means of compensating for variations of size of animals in an experiment.

Excretion and Body Size

Space does not permit any extensive excursion into the subject, but it is essential to our thesis as to the influence of variation in excretion rate on variation in body burden. There are extensive references on interspecies correlations between excretion rate and body size, ranging from microscopic marine organisms (Johannes 1964) to large ungulates (Ekman 1966). Some detailed studies are reported by Richmond and his associates (e.g., Richmond *et al.* 1962, Furchner and Richmond 1962).

Less attention seems to have been paid to the significance of excretion rate and weight correlations among groups of individuals of the *same* species, but differences are noted for snails by Mishima and Odum (1963), and for two species of small mammals by Golley, Weigert, and Walter (1965: 720). An analysis of the relationship for humans is given by Eberhardt (1967).

From the available evidence, we are inclined to suppose that principles of biological similarity (e.g., Stahl 1962) may be used to deduce quite general relations covering a wide range of species. A start in this direction is represented by the report of Fujita, Iwamoto, and Kondo (1966) who have considered interspecies relations of cesium and potassium metabolism to body weight in light of such factors as kidney-weight-to-body-weight equations.

Variability in Food Chains

Several lines of evidence suggest that coefficients of variation of radionuclide concentrations are relatively stable in natural systems (Eberhardt 1964). Some recent reports from the Nevada

Table 1. Coefficients of variation for ^{137}Cs in plants and animals in the Northwest (sample sizes in parentheses)

Source	Plants	Rumen Content	Muscle	Feces
Antelope (Wyoming)		0.078 (8)	0.239 (16)	
Domestic sheep (Wyoming)		0.147 (17)	0.297 (16)	
Elk (Montana)		0.147 (22)	0.268 (21)	0.273 (13)
Mule deer (Washington)		0.201 (29)	0.225 (47)	0.225 (19)
Douglas fir (Washington)				
Blue Mountains	0.200 (84)			
Cascade Mountains	0.200 (90)			
Agropyron spicatum (Washington)				
Blue Mountains	0.199 (62)			
Cascade Mountains	0.256 (18)			
Totals	0.203 (254)	0.160 (76)	0.248 (100)	0.224 (32)

Test Site demonstrate a considerable stability of variation, both in time and from plant to animal (e.g., Martin and Turner 1966: 625, and Martin 1965: 766).

Some interspecies comparisons are given in Table 1 for some Pacific Northwest plants and animals collected in a 1963 study (Eberhardt and Rickard 1965). Sample sizes given in the table pertain to totals, whereas the coefficients usually are weighted averages of sets of small samples (to avoid introducing seasonal and geographic effects). The use of small samples complicates statistical analysis considerably, so that we hesitate to attribute any special significance to the lower coefficient associated with rumen contents. The evidence seems clearly to favor a remarkable stability of relative variation.

Some fairly extensive samplings of elk feces obtained from different individuals in the same "bands" (groups) yield a mean coefficient of variation of 0.09, and in combination with other data (e.g., Eberhardt 1964) led to suggesting a hierarchy of variance components roughly as follows (Eberhardt 1966):

Source	**Coefficient of Variation**
Measurement ("instrument error")	0.05
Among individual organisms	0.10
"Small-scale" environmental	0.30 to 0.40

Discussion

Our efforts here constitute no more than an exploration of some prospects for deriving an uptake and retention model with a probabilistic basis. We feel confident that individual differences in excretion rates contribute largely to the observed variability, and present evidence suggests much of the difference between individuals is associated with differences in weight. But metabolic rates are certainly conditioned by many other factors in an individual's milieu — both internal and external.

We have wholly neglected the complications induced by the observed "compartment" effects, as well as questions of adsorption vs absorption, ingestion and assimilation, and so on. There seems little question but that uptake and retention in rapidly growing animals may differ greatly from that observed in mature or slowly growing individuals. For much of the growth period, body weight increases essentially exponentially with time, so that excretion rate experiments may be considerably complicated by concurrent decreases in the coefficient of any given individual. Space limitations prevent discussion of details, but further study of the data on ^{65}Zn in rainbow trout reported by Nakatani (1966) provides some support for this contention (Eberhardt and Nakatani 1968).

It seems evident, too, that daily intakes of a radionuclide may well not come from a "stationary" distribution, as assumed in our discussion of food-chain influence on variation in body burden. We speculate then, that the observed variability in body-burden from individual to individual living in the same general environment may need to be appraised in terms of at least three components: (1) that due to fluctuations in intake (stationary and non-stationary), (2) differences in metabolic rates associated with size, and (3) the usual mélange of small individual differences which contribute to "residual error" in a balanced analysis (plus, of course, errors of measurement and technique).

We would like to emphasize the hazards of "pooling" samples in analysis, in view of the consequent uncertainty as to effects of differences in excretion (and uptake) rates between individuals. It is perhaps instructive to note three distinct mechanisms resulting in excretion curves that will not plot as straight lines on semi-logarithmic paper: (1) excretion being due to the sum of several rates in the same individual, (2) changes in rate in time (e.g., the "Wiggins" model described above), and (3) "pooling" of samples of individuals having different rates. Our model for point (3) might, of course, also apply under point (1), if an individual has a sizable number of more or less discrete "reservoirs" or "depots" excreting independently at different rates.

Some instances in which the "modified power function model" seems to fit data very well and to have some qualitative justification include the following. Periphyton community studies conducted by C. E. Cushing (cf. Cushing and Porter 1969) show uptake and retention curves which follow the log-log plot very closely, and involve a sufficient diversity of constituents to make the basis for the model at least plausible. Similarly, Gutnecht (1965) exhibits excretion curves which plot almost exactly to straight lines on log-log coordinates, and notes the "non-uniform cell population in *Gracilaria* (cells range from about 10 to 600 μ diameter)." Another log-log decay plot for a mixture of components is reported by Whittaker (1961).

In an even more speculative vein, we wonder whether the diversity of storage sites and metabolites involved in the retention and excretion of pesticides might not yield similar results (as reported in the review by Hayes 1965). Further, pooling individuals in samples is regarded as a practical necessity by many analytical chemists. There is a considerable temptation to argue that other similarities should exist between radionuclide and pesticide behavior in ecological systems, both as a matter of general features and the casual observation of published data on relative variability (coefficients of variation on the order of 0.30 to 0.50).

Perhaps some mention should be made here of the frequency distribution of radionuclides in animal and plant populations. Nearly all the data we have seen shows clear evidence of skewness, and the log-normal distribution frequently is postulated as being appropriate. Perhaps the largest samples studied are those of Ellett and Brownell (1964) who now appear to favor the gamma distribution. In terms of qualitative arguments, we suppose that there are many situations where the notion of a random "waiting time" may be appropriate (e.g., exponential distributions of rainfall, Green 1964, or Barger and Thom 1949, Thom 1958, and the possible consequential effect on fallout distribution). On the other hand is the importance of growth, allometric, and similarity relations in which one might look for typically "multiplicative" effects, leading possibly to the log-normal (Cramér 1945). Better knowledge of the underlying mechanisms should provide a firmer basis for choice, or for various other distributions. There is, too, the applied statistician's point of view which must take into account a limited armory of analytical tools and often-conflicting needs (e.g., transformations for linearization vs those for equalizing variances).

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PART III. IONIZING RADIATION EFFECTS

Preface

Ultimately the concern of radiation ecologists is the effect of ionizing radiation on populations, communities and ecosystems. The concern is associated with the effects of varied levels of acute or chronic doses of ionizing radiation under varied circumstances on the structure and function of an ecosystem. Practically, repair mechanisms, patterns and rates are also of vital concern.

Most effects studies to date have been on populations and communities with major emphasis on acute radiation effects on various species. Further, the levels of ionizing radiation in the various studies have been greatly in excess of current fallout levels; thereby, necessitating use of radiation sources such as x-ray machines, cobalt-60 and cesium-137 to obtain either chronic or acute doses of ionizing radiation. An obvious weakness of our knowledge in this field stems from the fact that only a few of the Earth's major ecosystems have been experimentally irradiated _in situ_. This weakness is particularly apparent for aquatic systems.

The selected papers involve studies at waste disposal, nuclear test and experimental sites.

Ionizing Radiation and Homeostasis of Ecosystems

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This paper is a review of the concept of homeostasis as applied to ecosystems. It emphasizes the fundamental distinctions among various methods for the study of radiation effects on homeostatic mechanisms within ecosystems, presents one line of evidence for evaluation of these effects, and reviews the fundamental bases necessary for predicting effects of radiation stress on homeostatic mechanisms in other kinds of ecosystems. The paper is restricted to radiation effects *per se* with particular reference to nuclear war, and does not pertain to the distribution and fate of radionuclides in the natural environment.

A historical perspective is essential to understanding current concepts of homeostasis within irradiated ecosystems. Although most studies in the early days of the Atomic Age were medically or economically oriented, the significance of ionizing radiation as an ecological factor in man's natural environment did attract the interest of many biologists. Some of the first research programs were initiated in the 1940's at the Pacific Atoll test site,[20] and later at the Nevada test site.[16] The first major step in the development of radiation ecology, however, was the establishment in the mid-1950's of an Environmental Sciences Branch within the Division of Biology and Medicine, U.S. Atomic Energy Commission, to study direct effects of radiation and the fate of radionuclides in man's natural environment.

Among the first papers to attract widespread scientific and political interest was one of Wolfe's[18] on the ecological effects of nuclear war. Mitchell[8] presented perhaps the first Civil Defense analysis of ecological problems relating to postnuclear war recuperation. Studies were begun in 1956 at Emory University on radiation effects on ecosystems using primarily short-term exposures from point sources,[15] and in 1960 at Brookhaven National Laboratory using primarily continuous irradiation from point sources.[19] Many other programs, too numerous to review here, have been initiated in recent years. The First National Symposium on Radioecology was held in September 1961 under the auspices of the Environmental Sciences Branch of the USAEC and the American Institute of Biological Sciences.

This brief review shows that most of our concepts have been developed within the past ten years and that most publications on radiation ecology have appeared within the last five years. Today research on radiation effects on ecosystems, which involves homeostasis, is in a vigorous and actively expanding condition. With the broad outlines developed, the trend is toward research in greater depth, with increasing emphasis on physiological as well as ecosystem ecology.

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HOMEOSTATIC MECHANISMS

The term homeostasis is used to emphasize the concept that ecosystems have regulatory mechanisms paralleling those of organisms, and that ecosystems react to radiation stress in the same manner as to other environmental stresses. Utilizing these regulatory mechanisms, they adjust to continuously changing environmental conditions, including diurnal and other cycles, and react and adjust to various catastrophes.

Physical mechanisms affecting homeostasis include conditions of the physical environment such as temperature, moisture, light and ionizing radiation, nonliving materials, and energy flow. Structure refers to the spatial relationships of the various species, such as the trees and shrubs which form a closed canopy in deciduous forests, or the widely spaced plants of the desert, which form an open or interrupted canopy.

Species composition includes the diversity of species, the abundance and distribution of the component species, and the function of these species within the community in performing autotrophic or heterotrophic activities. In general, the greater the diversity, the greater the resources of the ecosystem in adjusting to stress. If certain species are removed by insect injury, extreme drought, ionizing radiation, or other stresses, the availability of replacement species becomes significant. Most ecosystems contain an ample supply of replacement organisms in the form of seeds and underground perennating organs. The removal or alteration of the overstory or other parts of the community changes conditions and presents opportunities for replacement organisms to establish themselves. These immediately available replacement organisms could have been left by prior successional stages or carried in by wind, birds, and other means. When an eastern deciduous forest is cut over, weed seeds that have been carried in by wind and other sources can germinate because of the changing conditions and within a matter of weeks and months re-establish a ground cover.

Tolerances to physical conditions, including ionizing radiation, temperature, moisture, and light, provide other homeostatic mechanisms unique to each species.

Still another ecosystem characteristic is productivity, which refers to the amount of energy fixed per unit of time. Earlier stages of succession are generally thought to be more productive than later stages because of the rapid change in species composition with time.

One of the most difficult homeostatic mechanisms to evaluate involves the biological interactions within and among populations. These include, for example, growth rate, growth form, age distribution, physiological state, competition, predation, and parasitism. Such interactions can vary widely and are constantly compensating so that over a long period of time there is a leveling off of species activities, even though fluctuations are essential to maintain the flow of energy, ample food supply, and other conditions within the ecosystem.

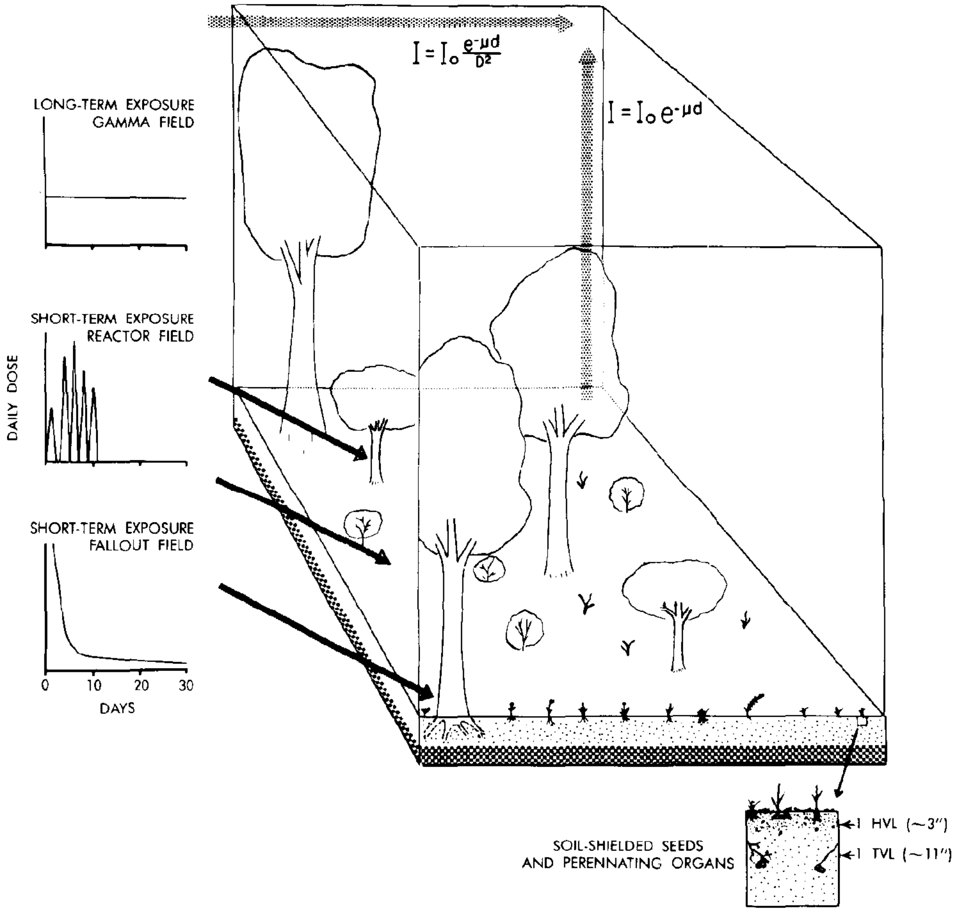
The important point in this brief discussion of homeostatic mechanisms is that ionizing radiation is an environmental stress on organisms and ecosystems, and as such must be considered as another environmental factor. This concept has been developed by Platt et al.,[12,13,15] Woodwell,[17,19] and others.

METHODS FOR IRRADIATING ECOSYSTEMS

Four basic methods, with many intermediate combinations, may be used for irradiating ecosystems. A three-dimensional model of an ecosystem, presented in terms of duration, dose rate, total dose, and dose distribution, is used in discussing these methods (Figure 1).

The methods are (1) short-term exposure from a uniform radiation field, followed by recovery; (2) short-term exposure from a point source, followed by recovery; (3) long-term or chronic exposure from a point source with concomitant adjustment to the continued stress; and (4) direct radiation from a nuclear explosion, accompanied by heat and blast, followed by recovery. In this paper, *acute* means exposure up to several hours; *short term*, exposure from several hours to several weeks;

Figure 1. A comparison of the radiation distribution from a point source and a fallout field. This three-dimensional model of an ecosystem demonstrates dose characteristics for two sources of radiation, one a uniform blanket of fallout, and the other a point source located away from the area studied. The lower right insert demonstrates environmental shielding of soil organisms, ½ of the radiation being attenuated by about 3 in. of soil, and 9/10ths by about 11 in. The inserts on the left show 3 kinds of dose rates over a 30-day period.



$I = I_o \frac{e^{-\mu d}}{D^2}$
$I = I_o e^{-\mu d}$
LONG-TERM EXPOSURE GAMMA FIELD
SHORT-TERM EXPOSURE REACTOR FIELD
SHORT-TERM EXPOSURE FALLOUT FIELD
DAILY DOSE
0
10
20
30
DAYS
SOIL-SHIELDED SEEDS AND PERENNATING ORGANS
HVL (~3")
TVL (~11")

long term or *chronic*, exposures of several months or more; *low-level* dose refers to doses in tens and hundreds of rads, and *high-level dose* to doses of tens of thousands of rads.

Short-Term Exposures From Uniform Radiation Fields

Fallout received as a uniform blanket on the surface of the ground would provide a "short-term exposure" (Miller, this symposium). The inverse-square law does not apply to such a uniform radiation field, and radiation dispersion is a function of the coefficient of absorption of the medium through which the radiation travels. Upward distribution of exposure is limited only by absorption by air and any vegetation that may be present. Distribution downward would be limited by absorption by the leaf litter and soil. Since the attenuation of upward distribution is relatively slight, dose distribution above ground from gamma irradiation is relatively uniform. Attenuation downward through the soil would be abrupt, however, the half-value layer for gamma radiation through soil being ≈ 3 in., and the $1/10$ value layer ≈ 11 in.

The distribution of beta radiation would be negligible, because of its high attenuation by air as well as soil. In the event of interception of fallout particles by leaves and twigs, the beta activity could be of some significance, because of its proximity to sensitive tissues in meristems.

Exposure rates and period of exposure are of particular significance. As shown on the left side of the diagram in Figure 1, the decay of fallout radioactivity is very rapid, two-thirds of the dose to infinity coming in two weeks. The exposure from fallout, then, is a short-term exposure by the definition used here. Recovery of the ecosystem would begin as the stress was relieved. None of our data suggests that the continued low-level radiation received from the decay of fallout particles after the first two weeks would have any significant effects on an ecosystem, although it may have some effect on certain species within the ecosystem. One example of this type of exposure is reported by Conard[2] at Rongelap. No serious effects were found in natural vegetation after exposures from fallout as high as 3000 r.

Short-Term Exposure From a Point Source

In certain experiments it has been convenient to use a single, centrally located source of radiation. Dose distribution in this case follows the inverse-square law, so that the attenuation falls off inversely with the square of the distance; there is also attenuation by the medium through which the radiation passes. If the distance from the radiation source were large in comparison with the distance across the area of interest, the change, according to the inverse-square law, would be relatively small, and dose distribution would approximate that received from a uniform fallout field, as in the case above.

Attenuation by the leaf litter and soil would follow the same general rule, since penetration into the soil is not greatly affected by the angle of incidence at which the radiation arrives. In the case of rough terrain, however, dose distribution below the soil may vary widely. Because of the buildup factor, as well as scattering by vegetation above the surface of the ground, it is possible that in some cases the dose will exceed that received above ground. (This is illustrated in Figure 3, where the dose distribution over the brow of a hill from the source increases along the surface of the ground relative to the line-of-sight dose because of scatter and buildup.)

If the duration of exposure is limited to a short term of a few hours or days, this system of radiation very closely approximates that received from fallout.

The Lockheed air-shielded reactor with its several hundred acres of irradiated ecosystems is the only large-scale example of this method.

Long-Term or Chronic Exposure From a Point Source

This method is similar to the one immediately above, with one exception. The stress here is continuous rather than temporary, and the effects are correspondingly quite different, since there is no opportunity for recovery as long as the stress is applied. An applicable expression would be "adjustment to the continued stress," with the ultimate consequence being that of a changed situation, with no chance at all of the area's returning to its original condition as long as the stress persists.

An ecological analogue of chronic exposures would be a hot spring, in which the ecosystem by adjustment to the continuously high temperature is quite different from other spring ecosystems. The continued exposure of an oak-hickory forest around a copper smelter at Copper Hill, Tennessee, ultimately resulted, after many years of continued stress, in a denuded landscape, including the top soil. In contrast, forests nearby that are occasionally subjected to intense fires still retain, following such a fire, essential elements of the ecosystem such as soil, and therefore retain the capacity to restore themselves to their original condition within a few years or decades. In another comparison, a deciduous forest climax under 35 in. annual rainfall would probably readjust to a prairie if the rainfall were reduce to 20 in. Likewise, a forest could survive a chronic irradiation stress of 300 r/day, but probably would readjust to a herbaceous ecosystem if the stress were greatly increased.[19] The irradiated forest at Brookhaven is the only example of this method. Radiation, started in November 1961, has been continuous and could be continued until a new equilibrium is reached. Results obtained after a few weeks or months exposure would be short-term data, but of course there would be no recovery.

Direct Radiation From Nuclear Explosions

Effects from this kind of radiation are very difficult to evaluate. The effects from the accompanying blast and heat have been in most instances more severe than that from radiation. Effects from these three stresses often are difficult to separate, and the radiation, coming in a flash, is a mixture of gamma, beta, and neutron doses. Subsequent irradiation of these highly disturbed ecosystems from the radioactive decay of materials in the area apparently produces minor effects in comparison to those above. However, in this case, as in the first two, recovery occurs as the stress is relieved. Atomic test sites provide many examples.[9]

FACILITIES AND EXPERIMENTAL DESIGNS FOR EMORY UNIVERSITY STUDIES

Facilities for the series of studies at Emory University consist of an outdoor gamma irradiation facility on the campus and the 10,000-acre reservation surrounding an air-shielded nuclear reactor operated by the Lockheed Aircraft Corporation. The radiation released into the environment around the air-shielded reactor has provided a unique situation. It is the only instance in which an ecosystem covering several hundred acres has been irradiated at exposures ranging from above-lethal to background levels over a period very closely approximating that which would result from fallout. It has the added advantage for our purposes of having received radiation of the order of tens of thousands of rads of accumulated exposure without the effects of heat and blast associated with bomb tests.

The Lockheed 10-MW reactor is in the center of a 10,000-acre reservation in the foothills of northern Georgia, an area of great ecological diversity.[10] The principal vegetation is mixed evergreen-deciduous forest on both moist and dry sites, flood plain forests, and old fields on both upland and flood plain sites.

The irradiated area within which definitive biological studies have been made extends 1000 to 3000 ft from the reactor, depending upon the terrain. The irradiated area is roughly equivalent to that contained within a circle 2000 ft in radius, or almost 300 acres.

This large area has provided a broad numerical base for statistical analyses. For example, the irradiated forest contained an average of 150 trees/acre. Since at least 250 acres of land were wooded, the number of trees >3 in. in diameter in the total experimental sample could be estimated at 37,500. Figures for shrubs and herbs are even more impressive. Sample numbers, therefore, of hundreds and

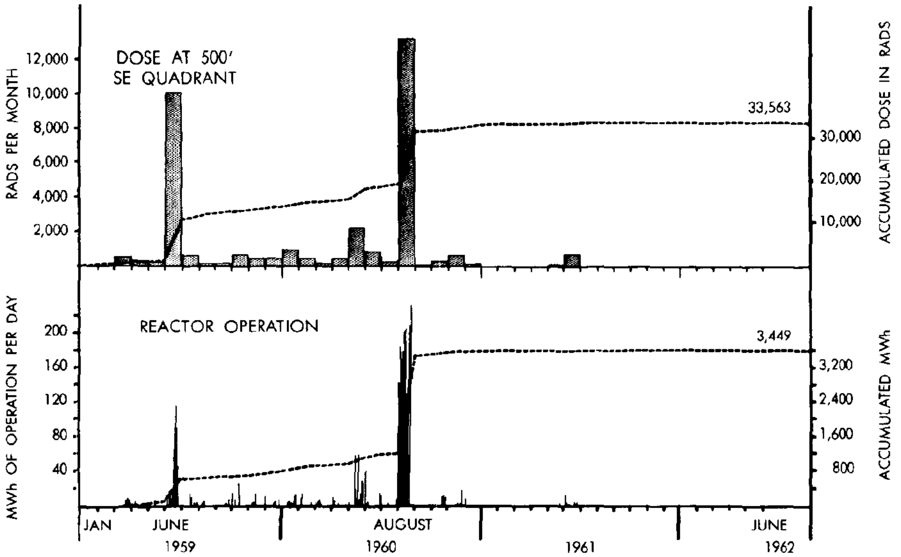


Figure 2. Lockheed reactor operation data beginning with the initial run. The schedule from June 1962 to the present has been approximately the same as that for 1961. Note that >80% of the radiation was released at two times, and that each time it approximated irradiation from fallout in both duration and total dose. At 500 ft, the dose each time was about that of the maximum expected over 2 to 5% of the United States from a 20,000-MT attack.

thousands per experimental plot have made it possible to distinguish between effects of ionizing radiation and those of other adverse environmental factors with which they may easily be confused, such as drought, killing frosts, insect damage, and disease. As these effects also occur in natural ecosystems, such distinctions are of extreme importance.

This large area provided radiation dosage gradients ranging all the way from accumulated doses over several months of 100,000 rads to background levels.

The distances at which biologically effective dosages were received were great enough that the decline in exposure with increasing distance from the source was relatively low. This means that exposure gradients across the crowns of large trees as well as across sizable experimental plots were very slight.

The irradiation pattern followed that of the second method above, short-term exposure followed by recovery.

By good fortune, >80% of the radiation released came in 2 short-term exposures of 2 and 3 weeks respectively, one in June 1959 and the other in August 1960 (Figure 2). The intensity and duration of each of these exposures were by chance similar to those expected from fallout following a nuclear catastrophe. The other 20% was delivered intermittently over a 3-year period at low intensities which had little or no effect at distances >500 ft from the reactor, except on selected species. Thus, the second exposure followed the first by 14 months, and 4 years have elapsed since then. This combination of exposures has provided unparalleled opportunities for observation of recovery over a 14-month period following the first exposure, and over a total of 5 years since radiation was first released.

Two years' study of the area was possible prior to the initial reactor operation, so that experimental plots, control areas, inventories of plants and animals, and other necessary preirradiation procedures could be carried out.

In order to test the observations made around the reactor site, a gamma radiation field was established on the Emory University campus as a control facility for the duplication of critical experiments under controlled conditions.

ECOLOGICAL DOSIMETRY

The expression *ecological dosimetry* is used to emphasize the unique nature of the dosimetry program developed in the rough terrain surrounding the nuclear reactor.[3] To sample adequately the distribution of radiation exposure throughout the 300 acres, over hills and across valleys, at various distances above ground as well as below ground, and at various positions within arboreal vegetation, detection stations were placed at 68 locations, each station consisting of a series of neutron and gamma-ray detectors. Twenty-three were in the reactor "line-of-sight," while the others were arranged to measure various types of shielding by vegetation and terrain.

Neutron activation detectors were used for the field measurements of neutron flux. Thermal and resonance neutron distributions were measured by reactions with cobalt, sodium, manganese, and gold detectors, while the fast neutron distribution was measured by using sulfur, thorium, and nickel threshold detectors. By using a series of these detectors at each field location, a neutron energy spectrum was constructed. The primary gamma-ray measurements were made with film badges used for the radiation monitoring of personnel, and with chemical dosimeters. These measurements were augmented with a selected number of silver-activated phosphate glass dosimeters. The film badges were used primarily for measuring low doses, while the other two types of dosimeter were useful for high doses. The accuracy of the chemical dosimeters for the dose rates and ranges encountered was within ±10%, while the accuracy of the film and glass dosimeters was within ±20% All dose measurements were expressed in rads (1 rad = 100 ergs/g).

In naturally shielded areas neutrons were attenuated proportionally more than gamma rays by vegetation. Conversely, the soil attenuated gamma rays proportionally more than neutrons. The terrain, however, always produced more total-dose attenuation than did the vegetation. This behavior is in accordance with what could have been anticipated on the basis of the scattering and absorption cross sections of soil and plant atoms for gamma rays and neutrons. In particular, it is believed that the large hydrogen content of plants is responsible for the proportionally large attenuation of neutrons in areas shielded by vegetation.

One of the most significant results of this study was the observation that large dosages result in locations that are partially or completely obscured from the direct beam of the reactor (Figure 3). This can be attributed to initial air scattering and subsequent scattering by terrain and vegetation. Predominant scattering of the radiation in the direction of the incident beams was also observed in shielded areas. Maximum radiation protection in shielded areas was afforded at locations adjacent to the ground level or on the back sides of trees, away from the reactor, and is at-

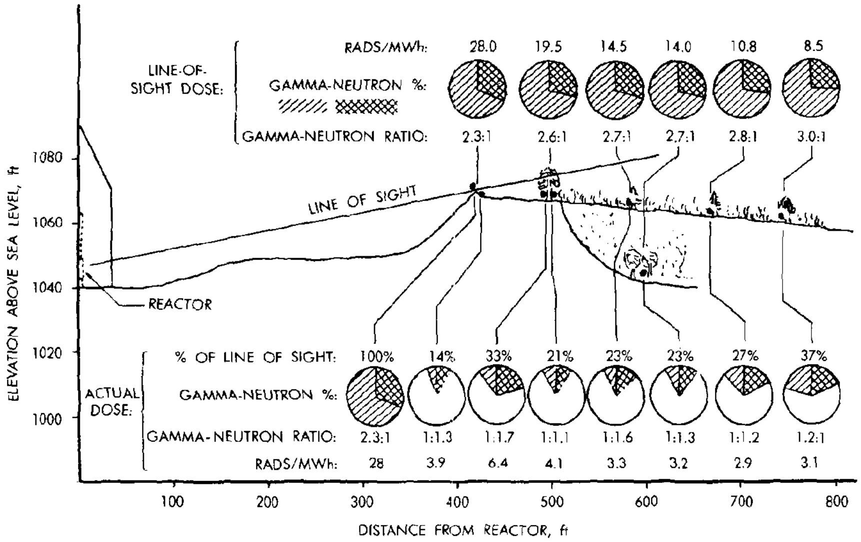


Figure 3. The effects of terrain and vegetation shielding on total dose for a line of stations ESE of the Lockheed reactor, located in a mature oak-hickory stand. The upper circles give the expected line-of-sight dose, while the lower circles give the actual dose, as reduced by terrain and vegetation shielding. Note exaggeration of vertical scale.

tributed to absorption by the ground and vegetation of a large part of the scattered radiation which would otherwise have contributed to the dose.

From the data of this study, it is possible to reconstruct the radiation history at practically any location in the radiation field and for any given period of reactor operation.

CHRONOLOGY OF EVENTS FOLLOWING IRRADIATION

A hypothetical example based on studies around the Lockheed reactor seems appropriate for this discussion of the potential effects of war. People leaving their fallout shelters in much of the temperate portion of the world in the last part of June 1959, following a nuclear attack from which fallout had delivered as much as 15,000 to 20,000 r of radiation, would be "pleasantly" surprised to find that the familiar surroundings of field and woodland looked as they did before the explosion. The one marked exception would be the areas in which pine trees were evident, for pines receiving 8000 to 10,000 rads or more would have begun to turn brown,

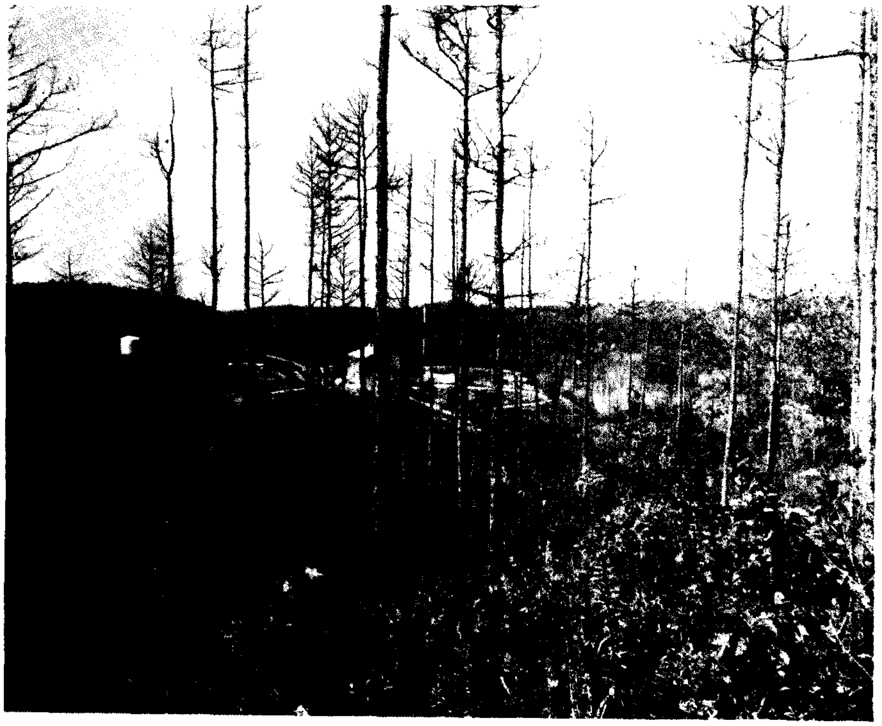


Figure 4. View toward the Lockheed reactor in July 1960, 13 months following the June 1959 exposure. These loblolly pines were dead 8 to 10 months following an exposure of >4000 rads. Removal of the pine overstory released the hardwoods underneath, which accelerated succession.

and in a few days would be a brilliant red-brown all over. If these were scattered through hardwood stands, they would stand out as bright flags in an otherwise apparently unchanged landscape. In fact, with the exception of damage to gymnosperms, there would be little change through the summer until August, when an unusually early leaf fall would be experienced. At least this is what happened in the several hundred acres around the Lockheed reactor. Obviously, these effects would vary as ecological conditions and physiological states within the ecosystem varied.

The relatively high sensitivity of pines (*Pinus taeda* and *P. rigida*) in contrast to the other woody plants was one of the most surprising of all observations, for this was the first time that pines had been irradiated. Within one week after the June irradiation, pine trees receiving doses of 7500 rads or more began to turn a brilliant orange-red and died within a few weeks. Those receiving about 4000 rads took much longer to die. In two years, most of those within 1500 to 2000 ft of the reactor were dead (Figure 4). Discoloration, death of terminal buds, and inhibition of reproduction by seed began with exposures >1000 rads. Apical meristems of pines were much more sensitive than lateral, and at certain doses when apical growth had stopped, radial growth seemed to be accelerated. Photosynthetic rates and tolerance to heat and drought were lowered by exposures of several hundred to several thousand rads.[11]

The second set of obvious effects on these ecosystems occurred in September when oak-hickory stands receiving 12,000 to 15,000 rads had a 7-week-early initiation of litter fall, followed by almost complete inhibition of leaf production the following year.[7] Oaks and hickories receiving 4000 rads had an early leaf fall of only

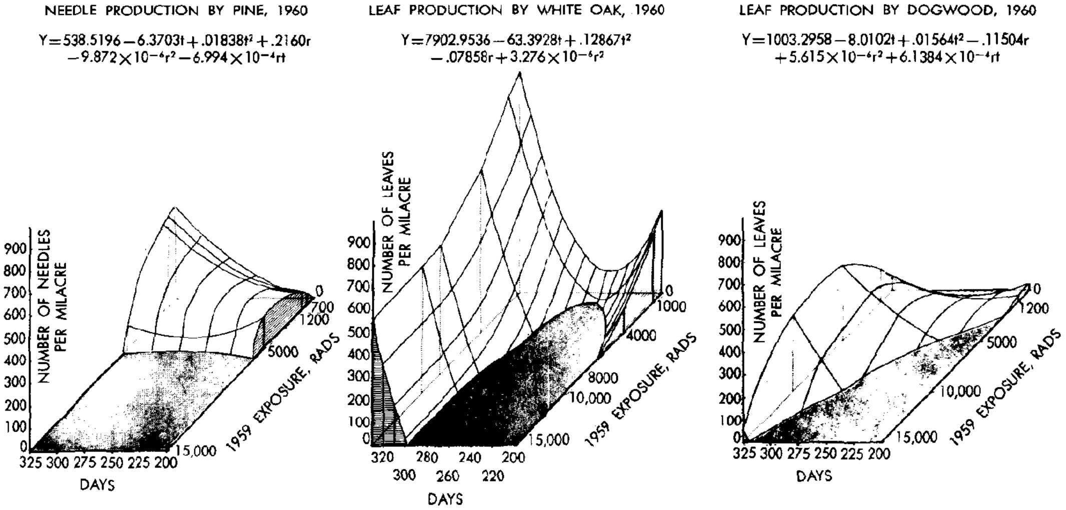


Figure 5. Three-dimensional response surface composed of regression lines for leaf production for three tree species as affected by the June 1959 exposure. Note relationships between time and dose along a transect 500 to1500 ft from the reactor. Reduction of the overhead oak-hickory leaf canopy released the more resistant understory dogwood, so that production for this species increased at the intermediate radiation doses. (From J.T. McGinnis, unpublished data.)

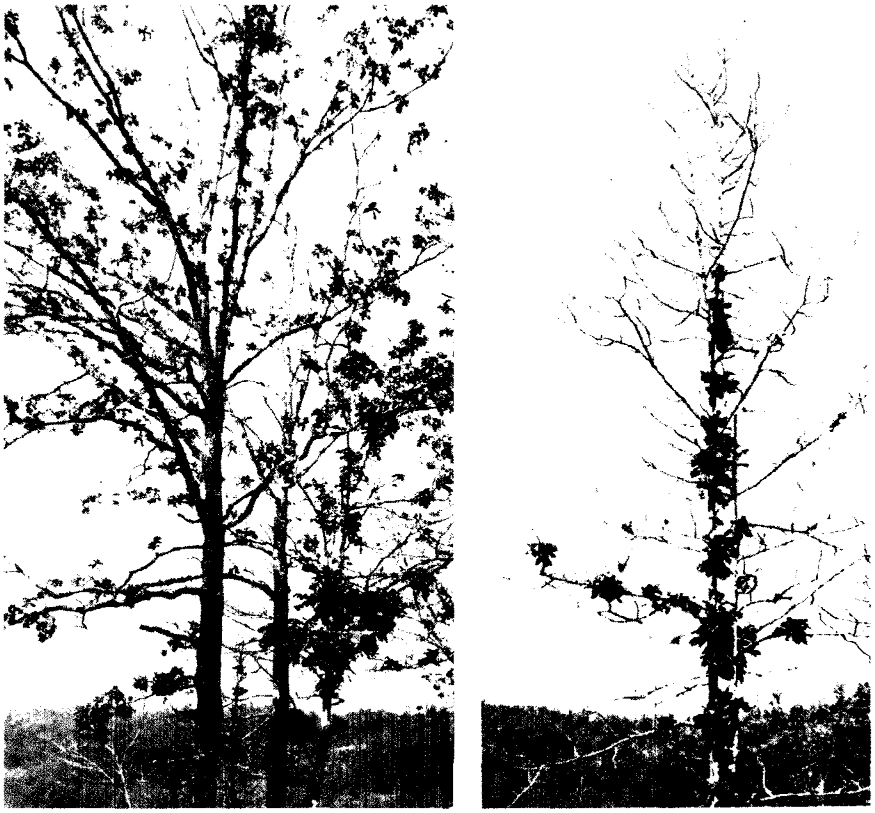


Figure 6. Photograph taken in July 1960, showing the effects of the June 1959 exposure. The white oak on the left received about 12,000 rads and the hickory on the right about 15,000 rads.

one week, as compared to nonirradiated stands, but leaf production was reduced to 39% the following year (Figure 5). Trees receiving 12,000 to 15,000 rads did not go through normal autumnal coloration, having lost their leaves early, while those receiving 4000 rads did go through a normal coloration.

The third set of effects was noted the following spring. In early April, when the hills of northern Georgia were bright with many hues of green due to the half-developed leaves of forest trees, an area up to one mile in diameter around the reactor was still in a state of winter dormancy. The prolongation of dormancy was proportional to the dose received, bud expansion being delayed from 1 to 2 weeks at doses of 10,000 to 15,000 rads. These effects were ascribed directly to the fact that the primordia of the estivating buds were already laid down in June of the preceding summer, but the radiation damage was not apparent until the buds expanded the following spring.

A fourth set of effects also appeared in the spring. On hardwoods receiving 3000 to 4000 rads, almost all the terminal buds were killed, and branches receiving

2 or 3 times this dose were killed back several inches. Almost all of these trees did develop lateral buds, but there was a very pronounced relationship between the severity of the dose and the position on the tree at which lateral buds appeared. Those receiving 3000 to 4000 rads had lateral buds developed on the same twigs on which the terminals had occurred, and, as irradiation increased, the buds developed on larger limbs so that those receiving 15,000 rads had only a few buds along the main trunk (Figure 6). In contrast, the lateral meristems in every case, including

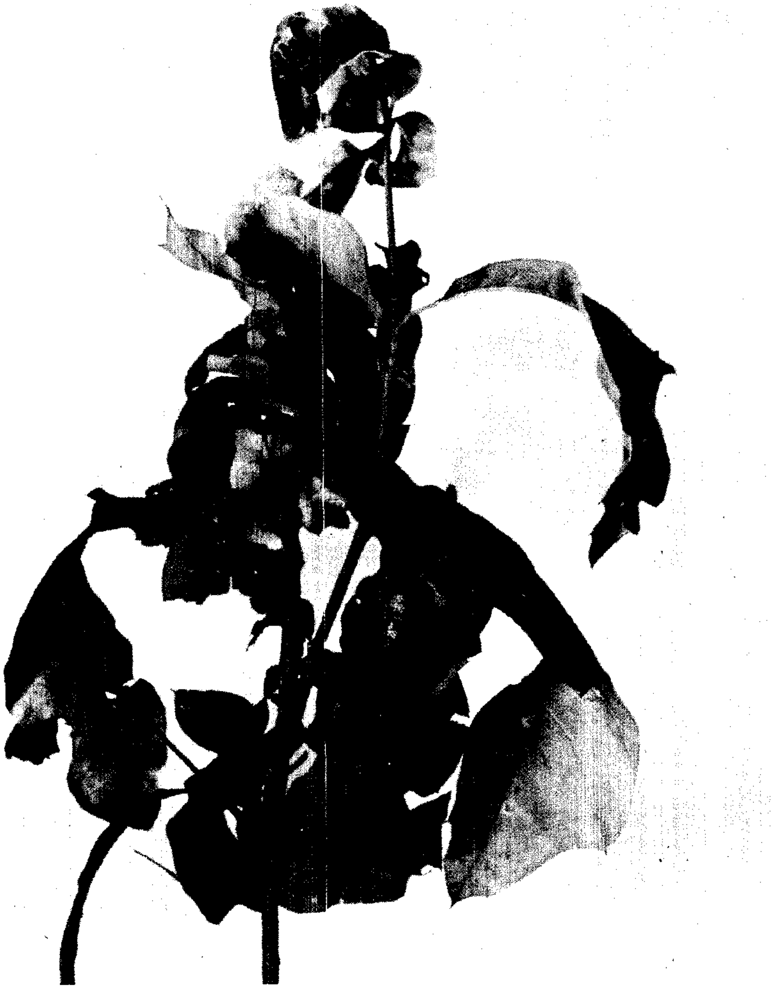


Figure 7. Photograph of a southern red oak branch taken in July 1960, showing typical hardwood response to the June 1959 irradiation. Note aberrant growth.

trees having the highest doses, were bright green and remained so through the spring and summer.

Another obvious manifestation was that almost every leaf produced from a tree on which the terminals had been killed was highly aberrant (Figure 7). Species differences for the most part were slight, but some trees, such as buckeye and sourwood, were markedly different in their responses.

In July of 1960, 13 months following the irradiation, pines that had received >4000 to 5000 rads were dead, and those that had received >2000 rads were markedly affected. Hardwoods receiving 10,000 to 15,000 rads had been devastated (Figure 8) and had only a few flags of leaves, whereas hardwoods receiving 4000 to 5000 rads had leaf production cut to ¼ or ⅓, but nevertheless produced growth adequate for survival. Hardwoods receiving less than this dose were little affected.

Effects on the vegetation of abandoned agricultural fields within the irradiation area may be grouped into three types of response.[4] First, species became arranged along the radiation gradient in successive dominance bands, according to their interacting tolerances for radiation, light, moisture, and other factors. Second, within a uniform radiation zone, elimination of a radiation-sensitive species occurred when that species aborted by tissue breakdown or was unable to complete its

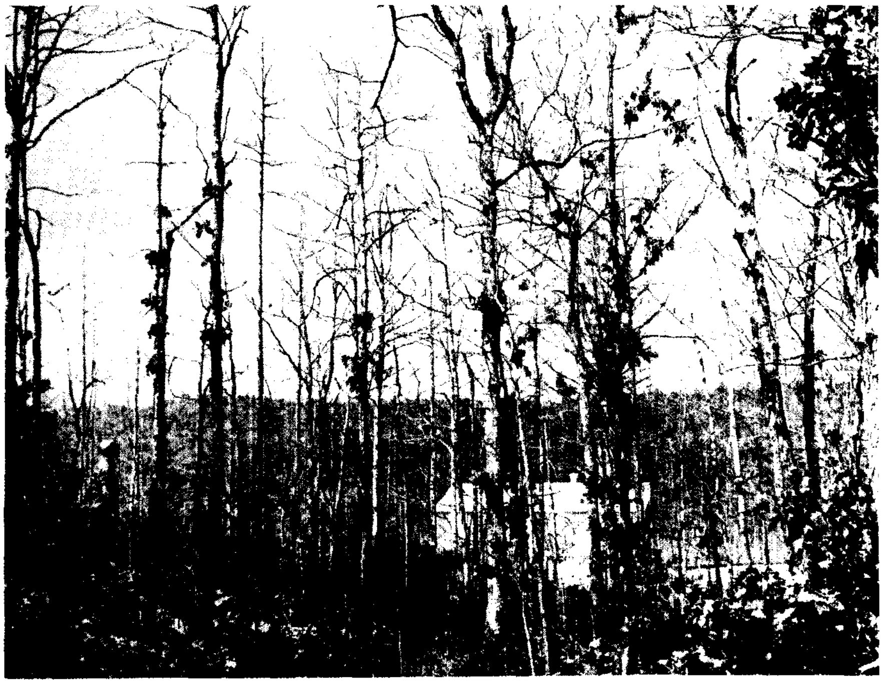


Figure 8. Photograph taken in July 1960, showing effects of the June 1959 irradiation on a mature oak-hickory stand. Doses ranged from 12,000 rads in the part closest to the reactor to about 8000 rads in the foreground. See Figure 12 for another view of this stand 3 years later.

life cycle. The resultant opening in the community was invaded by more radiation-resistant species which were able to complete their life cycles.

Third, perennials often held their position in the community by vegetative growth of perennating organs, although inviable seeds were being produced. Figure 9 shows a normal vegetational pattern for these fields over the first 5 years of succession. The over-all effect of severe irradiation was to throw the field back into an earlier stage of succession. As pointed out above, this was brought about by differential sensitivity of species and the concomitant change in the community structure. Although several experimentally established successional communities received 25,000 to 30,000 rads exposure, being fairly close to the reactor, at no time were these communities denuded. In fact a casual look would reveal no obvious effects, since these changes took place slowly over several months.

The second radiation exposure occurred over a 3-week period in August, 14 months after the first one. The same general kinds of effects occurred. This additional irradiation killed certain pine trees which had been damaged previously. Again, there was an early leaf fall which was roughly comparable to that of the preceding fall, and the following spring there was a comparable prolongation of winter dormancy, with killing of terminal buds and development of laterals.

This series of observations following the second exposure reveals one of the most interesting effects of the entire chronology. The effects of the second exposure were about the same as those of the first, which demonstrated that substantial recovery of

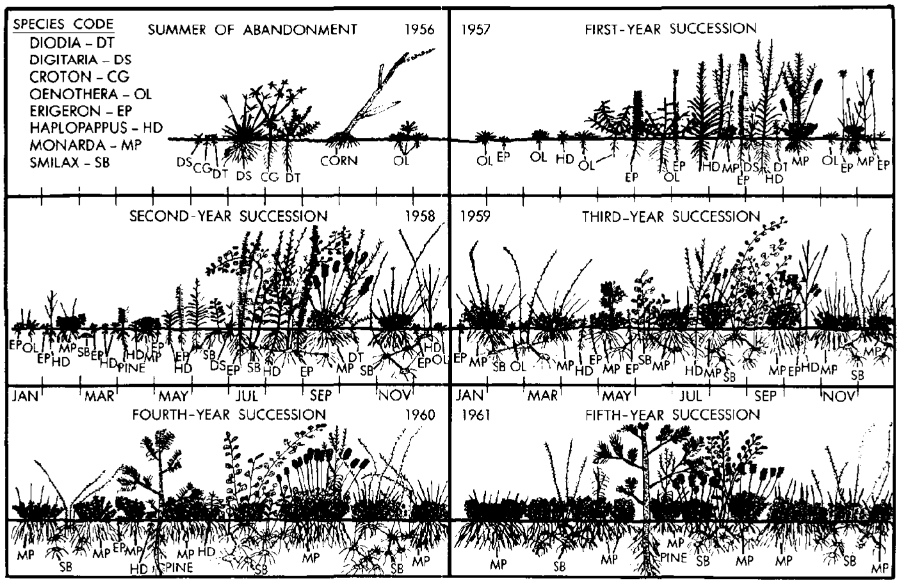

SPECIES CODE
DIODIA - DT
DIGITARIA - DS
CROTON - CG
OENOTHERA - OL
ERIGERON - EP
HAPLOPAPPUS - HD
MONARDA - MP
SMILAX - SB
SUMMER OF ABANDONMENT
1956
DS CG DT DS CG DT CORN OL
1957
FIRST-YEAR SUCCESSION
OL EP OL HD OL EP OL EP HD MP DS EP DT HD MP OL EP MP EP
SECOND-YEAR SUCCESSION
1958
EP OL EP HD MP SB EP HD PINE HD MP EP EP HD SB DS EP SB HD EP MP DT SB HD EP OL
1959
THIRD-YEAR SUCCESSION
EP MP SB OL MP HD EP MP EP SB MP HD MP SB MP EP HD MP MP SB
JAN
MAR
MAY
JUL
SEP
NOV
FOURTH-YEAR SUCCESSION
1960
MP SB MP EP MP HD PINE MP HD SB MP SB MP
1961
FIFTH-YEAR SUCCESSION
MP SB MP MP PINE SB MP MP SB MP

Figure 9. Diagrammatic representation of normal vegetation in the field adjacent to the Lockheed reactor. Radiation (up to 25,000 rads short-term dose) causes changes and reduction in species composition, with a corresponding shift to an earlier stage of succession. (From C.P. Daniel, unpublished data.)

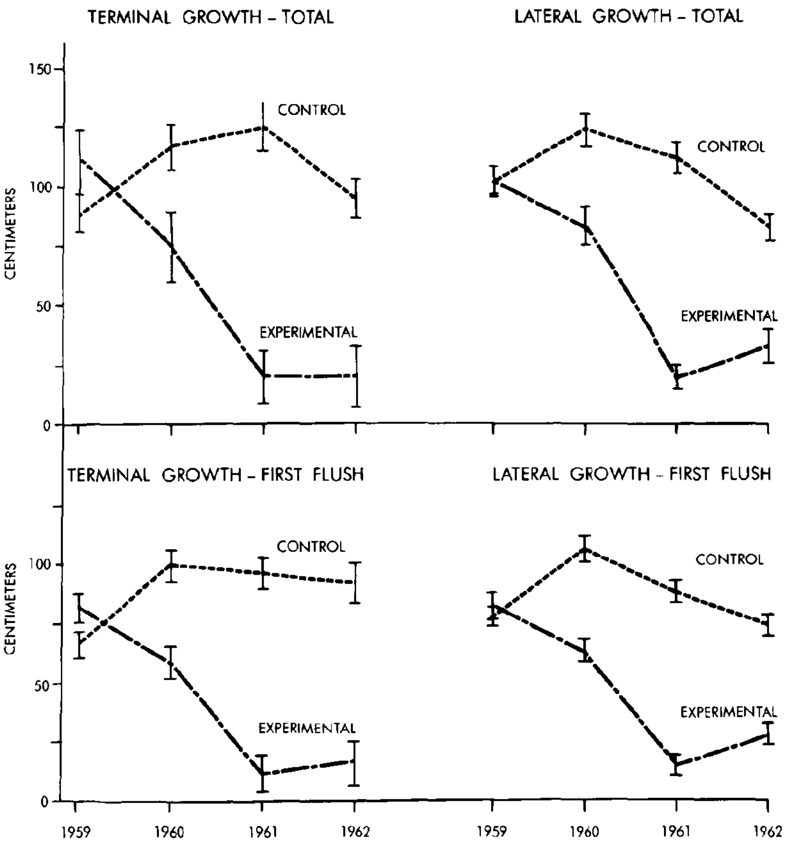


Figure 10. Graphs showing the effects of radiation on a pine stand receiving about 300 rads in June 1959 and 700 in August 1960. There was no visible evidence of damage. The crowns of 20 trees (10 from an experimental stand and 10 from an ecologically comparable control stand) were removed for study in August 1963. Of the 10,000 measurements obtained, those pertaining to four aspects of growth are analyzed. Vertical lines represent twice the standard error. Note that the June 1959 effects did not appear until 1960, and the August 1960 effects until 1961. With no irradiation in 1961, growth was normal in 1962.

damaged plants had occurred. Thus, the effects of the second exposure were not additive, except in those instances in which the trees were already close to dying, and this additional stress killed them, as a bad drought might. The delayed response in tree growth from summer to the following spring was widespread. Figure 10 graphically demonstrates this effect in pines receiving about 300 and 700 rads for the two irradiation periods.

Conditions during the summer following the second exposure were comparable to those of the first, with the exception of those areas in which the overstory had been killed and ground canopy removed (Figure 11). During the first summer this

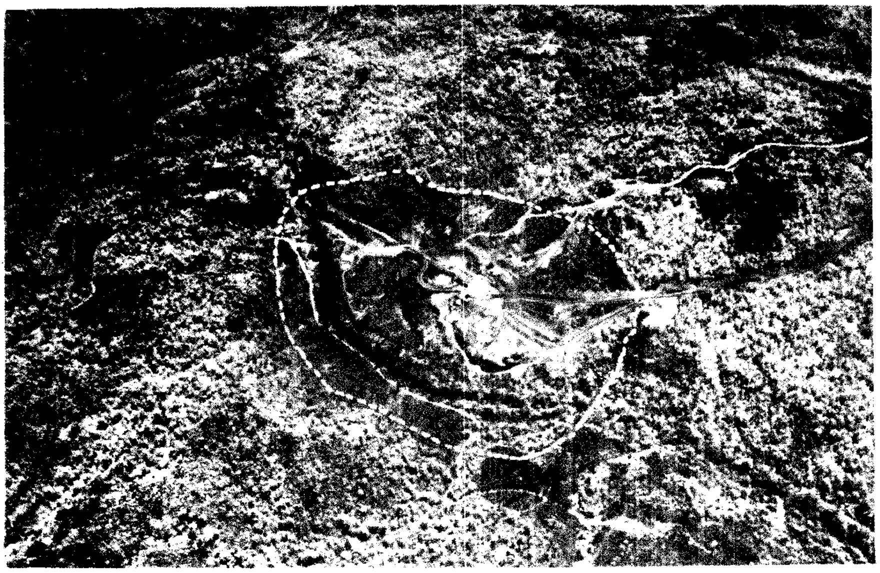


Figure 11. Infrared aerial view of the Lockheed 10-MW nuclear reactor located in the center of a 10,000-acre reservation. This photograph, taken in June 1961, shows the effects of radiation of the two preceding summers. The dotted line encloses the area of visible radiation effects, 800 to 1500 ft from the reactor.

floor under the opened canopy had demonstrated some sprouting from protected root crowns along with the growth of weeds whose seeds had probably lain dormant for many years on the forest floor pending a time at which conditions would favor germination and growth.

The weed flora was greatly increased the second summer because of the additional seed source from the first summer; at some points the weeds were 8 or 10 ft tall and almost too dense to walk through. The condition at that time seemed to indicate that these forests had been thrown back into an old-field stage and that normal old-field succession would now follow. However, in the third summer, root sprouts which had shown rather poor growth during the first two summers now began to develop rapidly and shaded out the weed flora before it had a chance to get well established. By the end of the third summer, hardwood sprouts began to dominate, and by the end of the fourth summer they had formed a closed canopy under which very few weeds were able to develop. This past summer, the fifth following the first irradiation, there was every indication that these sprouts would continue to develop and that the hardwoods would be restored (Figure 12).

In forested areas in which leaf production was reduced up to 50%, there was no great change in the forest community, with the exception of an increased number of ground-cover plants in the first two summers. Three summers following the first irradiation, the leaf canopy was increasing and leaf aberrations were minor, and by the fourth and fifth summers the trees had returned to a fairly normal appearance.

In the old fields, the areas that had been thrown back to earlier stages of succession moved forward without further interruption, and there was no continued evidence of irradiation damage. The extensive aberrations in leaves and the effects of suppression of reproduction, as in *Smilax*, disappeared and plants were growing normally.[1]

DISCUSSION AND CONCLUSIONS

Information gained over the past 9 years from experimental irradiation of small, manipulatable ecosystems, along with that from 7 years of study at the Lockheed reactor site, is now sufficiently complete to demonstrate some fairly clear-cut cause and effect relationships for short-term exposures, similar to those that would arise from fallout following a nuclear attack.

1. The patterns of effects and recovery in plant populations seem now well established; they are shown graphically in Figure 13. The dose in rads is given in the left-hand column for exposures of 15 to 90 days. The year of development of various

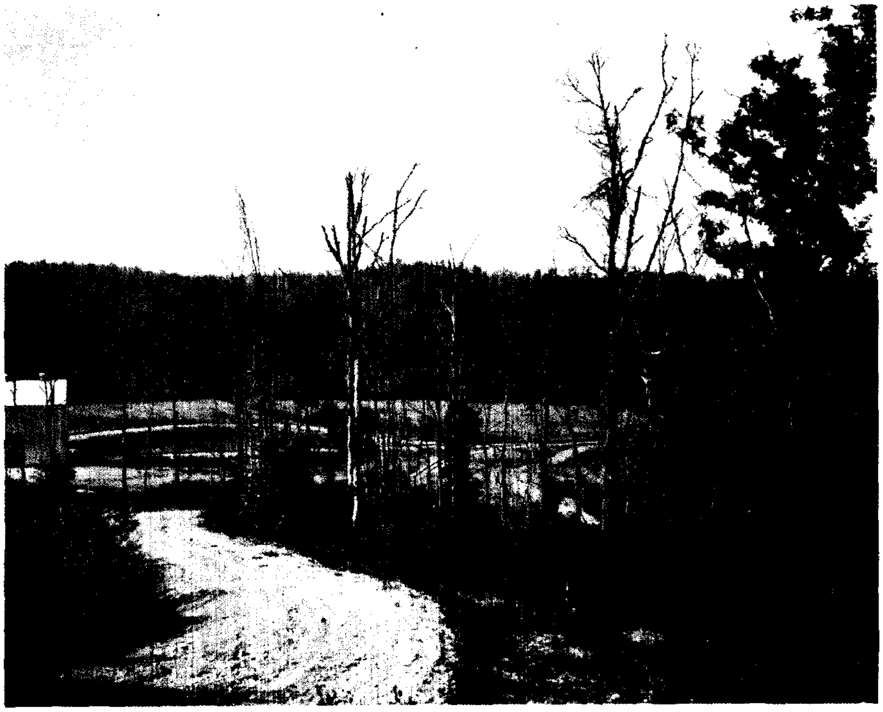


Figure 12. Photograph taken in August 1963 of the same area shown in Figure 8, three years after the second exposure. By this time trees have either died or begun recovery, intermediate stages disappearing. A flourishing growth of root sprouts seems to be returning the area directly to an oak-hickory forest.

AIR DOSE IN RADS, 15-90 DAYS	DEVELOPMENTAL STAGES								
	HERB			SHRUB			TREE		
	YEAR OF DEVELOPMENT								
	YEAR ABANDONED	1st	2nd	3rd	4th	5th	7th–12th PINE DOMINATION	12th–50th	OAK HICKORY PINE CLIMAX
0-1000	MINOR EFFECTS			SOME DAMAGE TO PINE					
1,000-3,000									
3,000-6,000				PINE SEEDLINGS KILLED			PINE KILLED; HARDWOODS RELEASED; SUCCESSION ACCELERATED		PINE KILLED
6,000-10,000	SHIFT IN DOMINANCE								
10,000-20,000				HARDWOOD SEEDLINGS KILLED			HARDWOODS KILLED; REVERSION BY SPROUTS TO HARDWOOD SEEDLING STAGE		
20,000-50,000									
50,000-100,000				REVERSION TO EARLIER HERB STAGE			ALL TREES KILLED; REVERSION TO HERB STAGE		
100,000-300,000									
>300,000	MIXTURE FROM WELL-SHIELDED SEEDS, CORMS, ETC.								

Figure 13. Ecological effects of short-term radiation exposure on temperate ecosystems, based on data from Emory University studies. Doses up to 300,000 rads are plotted against developmental stages from abandoned agricultural fields to climax forests.

ecosystems from the time of abandonment of agricultural fields to mature oak-hickory-pine climax forests is shown across the top. The results indicated would vary somewhat with the severity of other environmental stresses, the time of year of exposure, and other conditions.

Three ecologically significant community types have been studied: herbs, shrubs, and trees (Figure 13). Herb communities can withstand radiation up to >100,000 rads exposure without elimination of the ground cover. Data on effects from the higher doses were obtained in the campus radiation field. For the shrub communities, i.e., the third, fourth, and fifth years of succession, during which the pine seedlings become established, the pine seedlings would be killed by doses>3000 rads and hardwood seedlings by >10,000 rads. If the dose exceeded 25,000 to 50,000 rads, the remaining herb stage would revert to an earlier year of development.

In ecosystems dominated by pine trees, as they would be from the seventh year on, pines would be eliminated first, hardwoods next, and a reversion to a herbaceous stage probably would not occur until 50,000 rads had been received, the latter due to elimination of root sprouts. The extensive work of McCormick and Platt[5] on granite outcrop ecosystems supports these conclusions.

2. The application of the experimental results to larger geographic regions is difficult, because the irradiated area is an island in the midst of normally developed ecosystems. What would happen if these conditions extended over several hundred square miles, so that most of the areas would have limited access to recolonization by higher forms of life, such as mammals and birds, or by seeds which might be brought in by various agents? A second factor involved in interpretation is that the exposures reported occurred only during the summer. Had the irradiations come at other periods, would the sequence of events have been comparable?

There is a good probability that neither situation would significantly alter the course of recovery as reflected in these studies. The single best argument for this is that recovery of vegetation is not dependent only upon the transport of organisms from other areas. Around the reactor site, replacement of killed or severely damaged plants was accomplished by the growth of seeds and underground perennating organs which were there before irradiation.

With respect to the larger animals, it is reasonable to suppose that extreme injury would be limited to areas of tens or hundreds of miles across, and there would be large numbers of refugia receiving less than lethal doses, from which repopulation of seriously damaged areas could begin. While this might require some time, repopulation could occur.

The invertebrates for the most part have radiation-resistant or environment-shielded stages so that populations would become re-established in the same sense that plants would recolonize the area.

The question of wildly fluctuating populations of insects and other pests which would seriously affect the balance of nature following irradiation has been raised on many occasions. Our observations within these ecosystems suggest that great caution must be used in making such predictions. The effects from a forest fire might well be much more severe than the killing of hardwood trees in a comparable area by ionizing radiation. Yet from such ecological analogues as fires, population fluctuations usually have not been of the kind that would seriously affect man's ability to survive. Every time a tree dies in the forest, or a hurricane causes a severe windthrow and the canopy is changed, comparable wildly fluctuating populations of the microinsect fauna occur, but the ecosystem compensates for this in many ways.

3. Irradiation in itself does not eliminate ground cover or leaf litter. In fact radiation which would kill the overstory of hardwood forests would probably leave the underground portion of the ecosystem relatively undisturbed because of shielding from the soil, although there would be changes in the microenvironment in terms of light, moisture, wind, and relative humidity.[6]

Unless an accompanying fire removed the ground cover, erosion would not be a factor. In the event that fires swept through the area following irradiation, there would probably be the same kind of recovery that has been observed many times before as a result of fires which have sometimes covered several hundred square miles at one time.

4. Radiation stress, like other stresses, tends to throw the ecosystem back to an earlier stage of development. Furthermore, the time of year of irradiation is of great

importance, and some of the most significant effects may be delayed for many months.

5. Sufficient information is on hand from many sources to make general predictions for the effects of radiation on other ecosystems. There seems to be general agreement that a rough correlation exists between the ecosystem's structural complexity on one hand, and resistance to radiation on the other, sensitivity of individual organisms to radiation being the principal exception.

One probable ranking of ecosystems in increasing order of resistance to radiation stress would be: coniferous forests, rain forests, deciduous forests, grasslands, tundra, and desert. However, for predictions of greater reliability and depth, much more information is needed. Figure 14 gives the kind of information that ideally is required for each of the functionally significant species as well as for the ecosystem. Nuclear characteristics are applicable in determining the probable lethal dose. For lethal or sublethal doses, the effects are those determined in addition by hormone and other metabolic systems, physiological states, and interactions with other environmental factors. The latter involve the functional relationship of the organism to its ecosystem, and this in turn is related to the ecosystem's own characteristics.

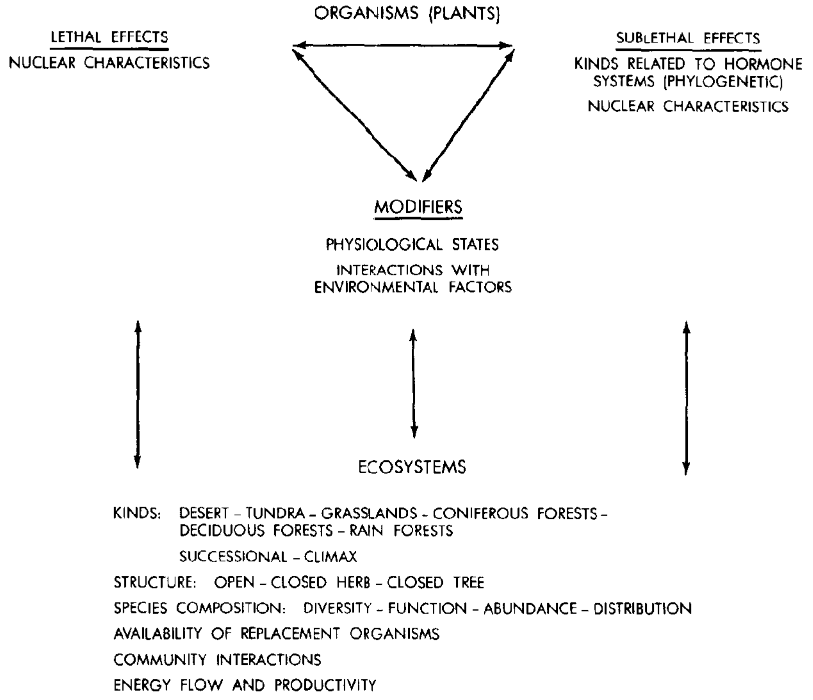

ORGANISMS (PLANTS)
LETHAL EFFECTS
NUCLEAR CHARACTERISTICS
SUBLETHAL EFFECTS
KINDS RELATED TO HORMONE SYSTEMS (PHYLOGENETIC)
NUCLEAR CHARACTERISTICS
MODIFIERS
PHYSIOLOGICAL STATES
INTERACTIONS WITH ENVIRONMENTAL FACTORS
ECOSYSTEMS
KINDS: DESERT - TUNDRA - GRASSLANDS - CONIFEROUS FORESTS - DECIDUOUS FORESTS - RAIN FORESTS
SUCCESSIONAL - CLIMAX
STRUCTURE: OPEN - CLOSED HERB - CLOSED TREE
SPECIES COMPOSITION: DIVERSITY - FUNCTION - ABUNDANCE - DISTRIBUTION
AVAILABILITY OF REPLACEMENT ORGANISMS
COMMUNITY INTERACTIONS
ENERGY FLOW AND PRODUCTIVITY

Figure 14. A scheme for homeostatic mechanisms that control radiation stress effects, the upper part relating to organisms (plants) and the lower to ecosystems. Conversely, an evaluation of these factors is revelant to the prediction of radiation effects.

EPILOGUE

Radiation effects and subsequent recovery in ecosystems near the air-shielded Lockheed nuclear reactor constitute the closest approximation of short-term radiation effects without heat and blast on vegetation. The two periods of high-level irradiation, 14 months apart, closely resembled fallout exposures, both in intensity and in duration. The course of recovery apparently has been well established in the five years since the first exposure and the four years since the second. Thus, it has been possible to establish ecological effects on vegetation for doses up to 300,000 rads, plotted against developmental stages from abandoned agricultural fields to climax forests. Since the pine-dominated stage is highly sensitive to radiation, the hardwood stage intermediately sensitive, and the herbaceous stage among the least sensitive, results from these three developmental stages have wide applicability to similar areas throughout the world.

In the event of a 20,000-MT attack on the United States with 100% fission, it has been estimated that 2 to 5% of the country would receive 15,000 r or more within 2 weeks, and 10% would receive 5000 to 10,000 r. The remaining 85 to 88% would receive $<$5000 r, the greatest percentage on the order of 1000 to 2000 r.

In view of these data, a broad generalization may be made for radiation effects from a nuclear war on this country's vegetation. From 5 to 20% of the forest ecosystems may have the tree overstory seriously damaged or killed. Another 20% may be visibly affected, but without the loss of the overstory; recovery for this percentage would be relatively fast. The damage may not be fully evident for several months to a year. If fire occurred, the damage would be increased. For the rest of the country (grasslands, deserts, and tundra), temporary changes may occur in the species composition in 2 to 10% of the area, the remainder being relatively little affected.

Therefore, direct radiation effects from nuclear war on vegetation are not likely to seriously limit man's reconstruction of his renewable resources. Other ecological effects may be far more limiting, such as radioactive contamination or effects on animals and food resources.

ACKNOWLEDGMENTS

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Effects of Ionizing Radiation on Ecological Systems*

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The surface of the earth is characterized by patterns described by natural vegetations such as forest, grassland, desert, and tundra, which together form a matrix within which man carries on agriculture and builds cities. These natural units are called ecological systems or ecosystems to emphasize that each is a well-integrated biological and physical system whose structure and function are governed by certain fundamental biological and physical principles. The purpose of this paper is to appraise the changes that ionizing radiation from nuclear war or another catastrophe might make in such systems.

Natural ecosystems maintain themselves by using solar energy alone; cities and agricultural ecosystems are maintained by man through input of energy which he controls. Discussion here is concentrated on major natural ecosystems.

Natural ecosystems develop continuously toward stability, or climax. This concept is basic to an understanding of the three patterns characteristic of ecosystems: (1) geographical patterns, defined by the regional climax vegetations, (2) successional patterns leading to these climax systems, and (3) patterns of internal structure and function.[35]

Detailed discussions of climax and of these three types of patterns are available in the works of Clements,[6] Oosting,[18] Braun-Blanquet,[3] Odum,[17] Braun,[2] and elsewhere. For the purposes of this discussion it is important to recognize that the principal elements of structure in terrestrial ecosystems can be classified conveniently on the basis of the species which dominate plant communities.

THE MAJOR ECOSYSTEMS OF NORTH AMERICA

Figure 1 is a map of the major vegetation types of North America: Tundra, Coniferous Forest, Deciduous Forest, Grassland, and Desert. The tundra and deserts contribute least to the welfare of man; coniferous and deciduous forests and grassland, on the other hand, form the major part of the matrix within which man, using energy from fossil fuels, controls his immediate environment with varying degrees of success.

Leading up to each of these stable vegetations is a regular sequence of developmental stages. Each stage is itself an ecosystem, having clearly defined structure and well-integrated function. Such successional patterns are complex and in most vegetations still poorly known except in very general terms. Woodwell[35] has illustrated

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*Research carried out at Brookhaven National Laboratory under the auspices of the U.S. Atomic Energy Commission.

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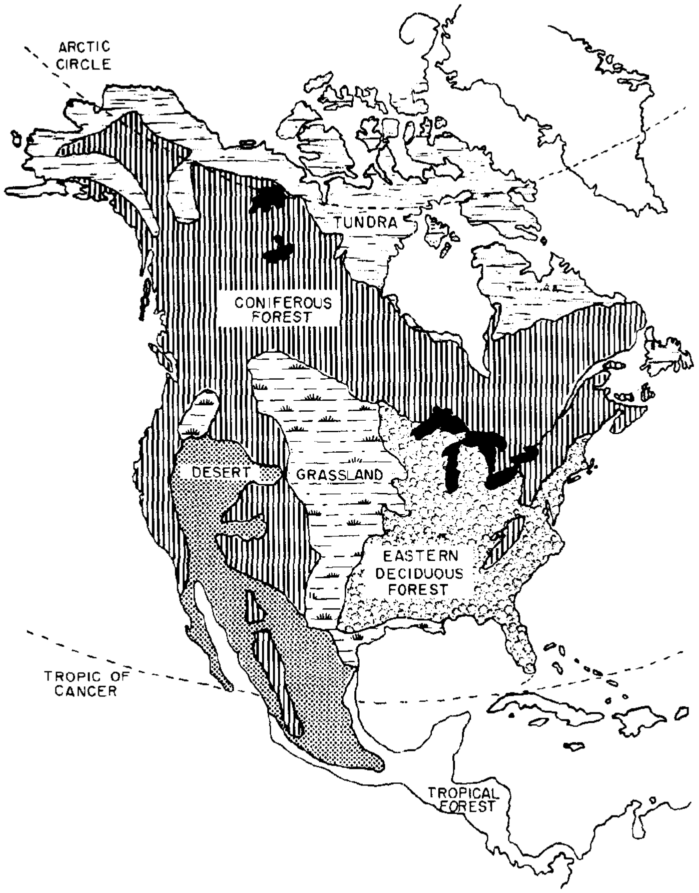

Figure 1. Major vegetation types of North America. Vegetation dominates the structure of terrestrial ecosystems and provides the basis for differentiating geographical patterns.

a successional sequence characteristic of the Eastern Deciduous Forest of North America by plotting approximate values for the accumulation of fixed energy against time. The graph for this vegetation is a sigmoid growth curve with the grand period spanning the first 50 years. Disturbance of a climax or lower stage sets the succession back along this curve, the speed and nature of the recovery depending on many factors, including climate, vegetation type, and season, as well as on the nature of the disturbance.

The patterns of internal structure can also be examined conveniently by using the distribution and flow of energy.[35] If only the energy fixed by the plants in a stable system is considered, energy losses in any year through export and respiration approximate the amount of energy fixed (Figure 2).

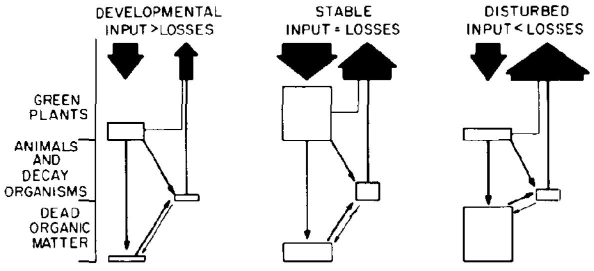

Figure 2. Energy flow through terrestrial ecosystems. In a stable or near-climax system, energy fixed approximates energy lost. In disturbed systems, losses may temporarily exceed fixation. In successional ecosystems, fixation usually exceeds losses.

Energy is retained within the system in three main categories: living green plants, dead organic matter, and the bodies of the consumers. Disturbance by fire, disease, or any other type of catastrophe such as high levels of ionizing radiation causes transfer of stored energy from the compartment representing green plants to the compartment representing dead organic matter. Following such a change a shift in consumer populations is expected to favor those feeding on dead organic matter as opposed to living green plants. Within a few years there is recovery of the plant populations, possibly augmented by invasion of species from outside the damaged area, and energy fixed in any year then exceeds energy lost. This is a developmental ecosystem, one of the stages leading to climax (Figure 2).

EFFECTS OF IONIZING RADIATION ON PLANTS

Classical descriptions of the effects of ionizing radiation on plants have usually recognized two types of effects: (1) genetic, and (2) somatic or physiological. A large body of recent research on plants has shown that both categories are probably due primarily to damage to the hereditary material. The importance of this relationship was shown recently by Sparrow, Cuany, Miksche, and Schairer[25] and by Sparrow and Miksche,[26] who demonstrated that plants with large nuclear volumes are generally more sensitive to radiation damage than plants with small nuclear volumes. These two categories of effects, then, are really differences in the manifestation of damage, the one involving mutations with minor immediate effects on growth or form, the other probably also involving mutations but showing immediate changes in function, including reduction in rate of growth, reduction in fertility, and possibly even an increase in mortality.

At the ecosystem level effects can be expected to parallel these and to involve (1) changes in the frequency of mutations and (2) changes in the vigor of the organisms irradiated.

It is well known that exposure to ionizing radiation produces an immediate increase in the frequencies of deleterious mutations.[30] Most of these mutants, however, are not new to the population; they also occur spontaneously in the natural population at some low rate, and any exposure to ionizing radiation can be expected to increase their frequencies. But if there is no long-term change in mutation rate, and if crossing is at random and selective forces within the ecosystem remain unchanged, then gene frequencies would become stabilized at the preirradiation levels within a few generations in accordance with the Hardy-Weinberg equilibrium. While there is real question as to whether all these conditions would hold following a nuclear catastrophe, it is probably true that any stimulus to evolution[13] would be of relatively minor importance.

It therefore appears that the principal immediate effects of fallout radiation would be those pertaining to the survival and vigor of the organisms irradiated. Selective elimination or inhibition of the most radiosensitive organisms would reduce the diversity of species in the ecosystem.[35] Such simplification, whatever the cause, starts a chain of secondary effects which include large immediate increases in the surviving populations that have the capacity for rapid growth or reproduction. These populations include both plants and animals, but include in particular small organisms such as the decay organisms and the insects because of their rapid reproduction, small size, genetic diversity, and mobility. Simultaneously, with the expansion of these populations invasion may occur from outside the area affected, and a new succession toward stability begins. This generalized pattern applies to a disturbance of any sort. The objective here is to define the radiation exposures that would trigger this well-recognized syndrome in major North American ecosystems.

BASIS FOR ANALYSIS OF RADIATION EFFECTS IN ECOSYSTEMS

Data available for such an analysis are of two types: data from radiobiological studies at the cellular and organismal levels, and data from field studies of irradiated ecosystems. A third possibility is the use of data from other major catastrophes not related to ionizing radiation as a basis for inference concerning recovery from radiation effects. We shall consider principally the first two of these.

CORRELATION BETWEEN CELL NUCLEAR CHARACTERISTICS AND RADIOSENSITIVITY

Of the data from radiobiological studies the most promising relationship for field application is the correlation shown by Sparrow and his colleagues between the volume of the nucleus or chromosome and radiosensitivity (Figure 3). Use of this correlation has made it possible to predict within broad limits the sensitivity of plants to damage from ionizing radiation.[23,24] Sparrow and Woodwell[29] predicted the effects of one year's radiation exposure on an oak-pine forest. Woodwell and Sparrow[37] reported that this prediction was substantially correct, although plants in this forest were generally more sensitive than anticipated. Precision in prediction apparently depends upon incorporation of additional information, such as data on the rate of cell division, stage in the life cycle exposed, the end point measured, and various environmental conditions as well. Despite these variables, estimates based upon nuclear or chromosome volume alone have frequently been accurate within a factor of 2 to 5. Since the potential variability among higher plants spans a factor of several hundredfold, this type of estimate is of substantial advantage.

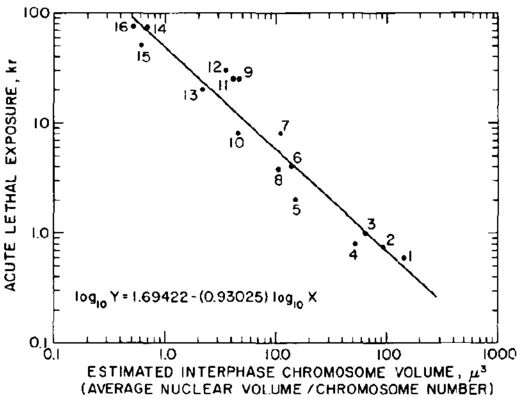

Figure 3. Relationhip between calculated interphase chromosome volume (nuclear volume/chromosome number) and acute lethal exposure for 16 species of plants: (1) *Trillium grandiflorum*; (2) *Podophyllum peltatum*; (3) *Hyacinthus orientalis* HV Innocence; (4) *Lilium longiflorum*; (5) *Chlorophytum elatum*; (6) *Zea mays*; (7) *Aphanostephus skirrobasis*; (8) *Crepis capillaris*; (9) *Sedum ternatum*; (10) *Lycopersicum esculentum*; (11) *Gladiolus* HV Friendship; (12) *Mentha spicata*; (13) *Sedum oryzifolium*; (14) *S. tricarpum*; (15) *S. alfredi* var. nagasakianum; and (16) *S. rupifragum*.[27]

FIELD STUDIES OF IRRADIATED ECOSYSTEMS

Data on radiation effects on ecosystems are limited to a relatively few field studies of ecosystems which have been irradiated experimentally. At the Pacific bomb test sites and at those in the North American desert, radiation effects have usually been confounded with the effects of blast and heat, and clear recognition of the influence of ionizing radiation has not been possible.[1,9,19,22,22a] The work of R.B. Platt[20] and his colleagues in the radiation-damaged areas around the Lockheed reactor in northern Georgia is discussed in the next paper. This series of studies is an important contribution to recognition of the potential effects of radiation on natural ecosystems.

At Brookhaven during the past two years a case-history study of an irradiated forest ecosystem has been under way.[34] The source of radiation is 9500 curies of Cs^{137} centrally located in an oak-pine forest which was selected because of its relative homogeneity. Exposure rates range from several thousand r per day within a few meters of the source to 1 to 2 r per day at 125 meters and on down to background levels. The forest has been irradiated for 20 hr daily since November 22, 1961.

DESCRIPTION OF THE EFFECTS OF A SIX-MONTH EXPOSURE OF A FOREST

Vegetation

The condition of the irradiated forest after six months of exposure has been described by Woodwell.[33] The major change in structure occurred at exposures in

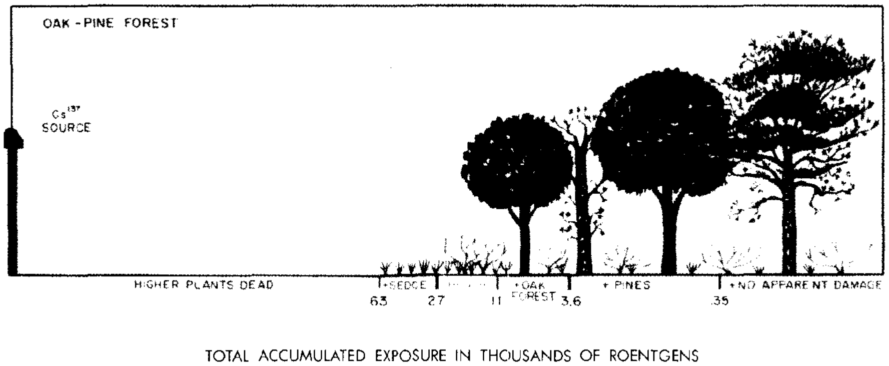

Figure 4. An oak-pine forest after six months' exposure to chronic gamma radiation.

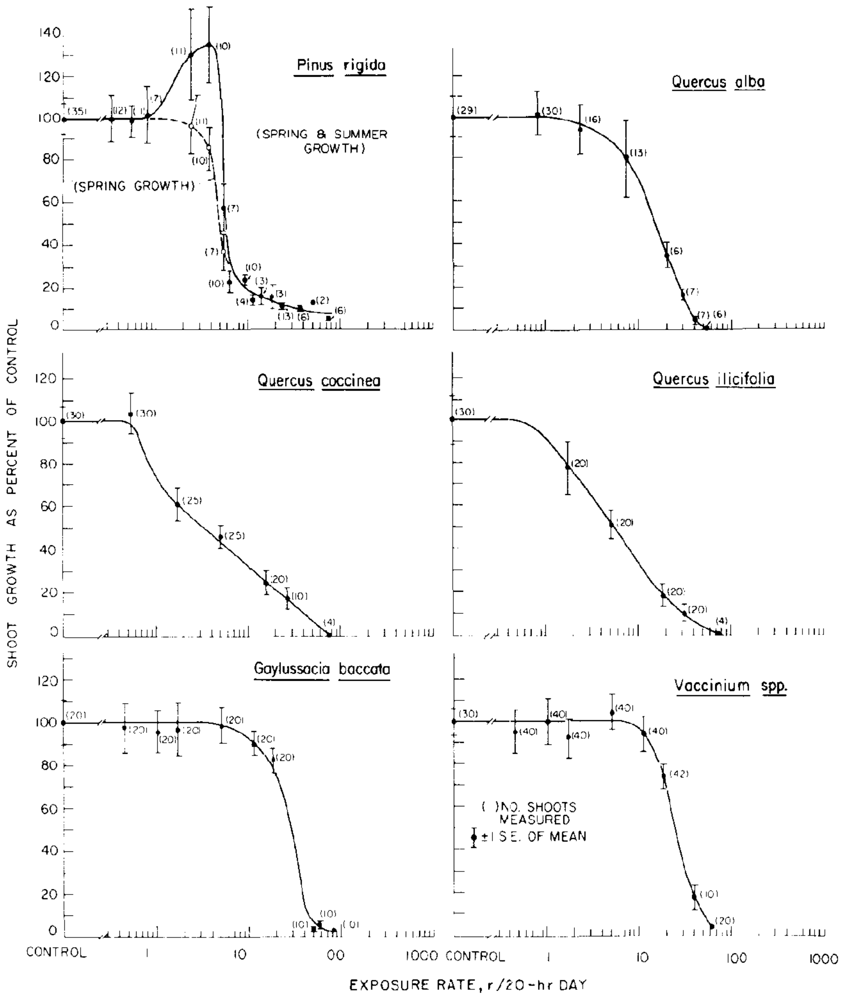

Figure 5. Growth of woody species in a chronically irradiated forest during the first year (1962) following installation of the radiation source.[17]

excess of about 60 r per day (11,000 r total), which killed the above-ground parts of most trees. Trees that appeared to have survived exposures in excess of 60 r per day had shielded buds which therefore were exposed to lower doses than average for that location.[11,34] These results are summarized in Figure 4.

At 23 r per day cumulative exposures of about 4000 r reduced foliage production of pine (*Pinus rigida*) (nomenclature follows Fernald[8]) to $<10\%$ of nonirradiated controls. Similar damage occurred in oaks (*Quercus alba*, *Q. coccinea*) at about 60 r per day (11,000 r total). The heath-shrub ground cover (*Vaccinium angustifolium*, *V. vacillans*, and *Gaylussacia baccata*) survived to about 150 r/day (27,000 r total) and the sedge (*Carex pensylvanica*) to $\approx$300 r/day (60,000 r total). Exposures in excess of about 63,000 r (350 r/day) killed all the higher plants of this forest, and the central area around the source supported only one or two individuals of *Baptisia tinctoria*, *Solidago*, and *Apocynum* during the summer of 1962.

As would be expected, shoot growth of the major species was inhibited by much lower exposures (Figure 5). Less than 10 r/day (1800 r total) reduced shoot growth of all tree species below that in a nearby unirradiated forest. Exposure of pine trees to 1 to 5 r/day (180 to 900 r total) caused a second flush of growth in midsummer, which resulted in greater shoot elongation for the year, but at higher exposures growth was inhibited (Figure 5).

The heath-shrub ground cover showed little damage at exposures <10 r/day (1800 r total). *Carex pensylvanica* was substantially more resistant. This plant reproduces rapidly vegetatively and within two years formed an irregular but extensive mat in the zone where other higher plants had died. Other evidence has shown that much smaller total exposures would produce equivalent effects if administered in a shorter period such as days or hours as opposed to months (see below).

Insect Populations

Insect populations in this experiment have been studied by Brower,[5] who made standardized sweep samplings of the shrub layer during 1961 prior to the establishment of the source and in 1962 and 1963 after irradiation was started. These samplings were supplemented by extensive systematic observations accompanied by limited sampling of other populations. The data have shown in general that the principal changes in insect populations have followed changes in abundance of food. The bark lice (*Psocoptera*), for instance, which feed in part on fungi, and the bark beetles (*Ips*), which inhabit dead and dying pine trees, increased in abundance in the zone of tree mortality. Populations of leaf hoppers (*Scaphytopius*), however, were depressed where the cover provided by blueberries and huckleberries was reduced by radiation damage.

In certain instances there was a clear increase in the amount of damage by herbivorous insects. Woodwell[33] reported an increase in the abundance of defoliators on radiation-damaged white oak trees during the summer of 1962. This increase was tentatively attributed to the concentration of endemic populations on the smaller total leaf-surface area of radiation-damaged trees. During the summer of 1963, the second summer following commencement of irradiation, exceptionally high populations of aphids occurred on leaves of radiation-damaged oaks.[5] These populations were more than 200 times as great as those in a similar nearby non-irradiated forest, which suggests that for some reason aphid populations were more successful on damaged trees. While the insect damage to surviving plants was conspicuous, the aphid populations declined later in the summer, and no evidence was found in this study that the biological interactions that are normally part of an orderly succession had been upset in any persistent or catastrophic way.

DESCRIPTION OF EFFECTS OF A SIX-MONTH EXPOSURE OF AN OLD FIELD

The effects of chronic gamma irradiation of an old field ecosystem at Brookhaven National Laboratory have been described elsewhere.[35,36] The results agree in general with those of McCormick and Platt[15] and Daniel.[7] Figure 6 is a summary of the results of the first year's observations of the old field, with total exposures covering the same period as for the forest (Nov. 22 – May 22). This treatment of exposure seems reasonable since the field contained only annuals whose seeds were probably distributed during the fall of the previous year[31,36] and were exposed on or near the surface of the soil during the winter. The exposure required to reduce diversity in the herbaceous plant community to 50% was $\approx$1000 r/day (total, 100,000 r), or $>$5 times the exposure required to produce a similar effect in the forest. Clearly the plant populations of this old field ecosystem are substantially more resistant than those of the irradiated forest.

COMPARISON OF BROOKHAVEN FIELD EXPERIMENTS WITH POTENTIAL EFFECTS FROM FALLOUT

Dr. Miller has described in this symposium the nature of the radiation in fallout fields, which differs qualitatively and quantitatively from the radiation fields of the

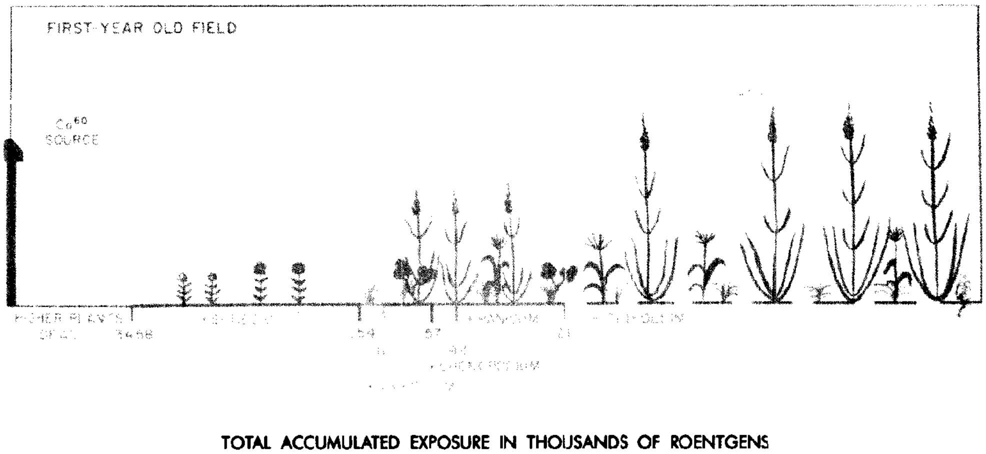

Figure 6. A first-year old field plant community which developed under daily gamma irradiation at levels that in six months gave total exposures shown.

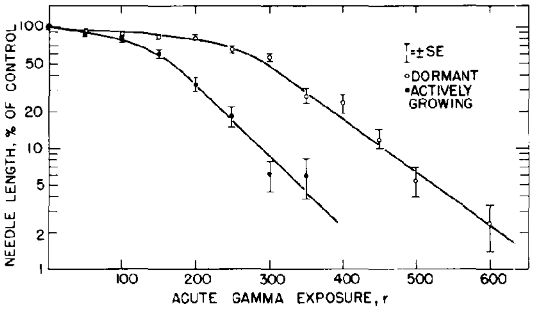

Figure 7. Needle growth of acutely exposed pine (*Pinus strobus*) during active growth and during dormancy.[28]

Brookhaven experiments. First, the exposure rate in a fallout field diminishes rapidly, dropping within 100 hr to $<1\%$ of the rate 1 hr after the blast. Dose rate is well known to be an important factor in radiobiology.[21] Second, the fallout field contains both gamma emitters and isotopes producing alpha and beta emissions. These latter emitters may have important effects not only after the radionuclides are incorporated into living material, but also when they are deposited on the surface of sensitive structures such as poorly protected buds or other meristems. Furthermore, while there would be local geographic variation in the amount of fallout, the general effect would be to blanket large areas with exposures relatively much more uniform than those of the experimental fields. These areas would be of the order of tens to hundreds or possibly even thousands of square miles.[16] This is of particularly great significance to considerations of the reinvasion of the devastated area by plants and animals in the recovery period. By contrast, the radiation in the Brookhaven experiments is entirely gamma from a single source of approximately constant size, and the area devastated is small and subject to reinvasion from the less disturbed areas nearby. Despite these important differences, the first year's results from the Brookhaven experiments, together with other data on radiosensitivity of species, provide a firm basis for appraising broadly the potential effects of fallout radiation from bombs on ecosystems. The experiment is particularly well suited for appraisal of effects on plant populations and on populations of sessile insects, less well suited for study of small mammals or motile insects.[34]

RELATIONSHIP BETWEEN SIX-MONTH CHRONIC EXPOSURE AND EXPOSURE FROM FALLOUT

The relationship between the exponential decay curve characteristic of fallout radiation and the chronic and acute exposures used in most experiments with radiation effects is difficult to resolve in a thoroughly satisfactory manner, since the degree of damage produced is a function not only of dose rate, but also of inherent characteristics of the organisms and of environmental conditions during and after exposure.[23,29,33,35] It is true, however, that the "acute" exposures of hours to a few days' duration are better approximations of the fallout exposures than chronic exposures.

Furthermore, total exposures administered chronically exceed in general the acute exposure required to produce the same effect by factors which may be as high as 20 or more. Perhaps the best index of the difference between the chronic exposure of six months and an acute exposure required to produce the same effect is provided by data on pine. In the irradiated forest, for example, >90% of the pines were dead in September at exposure rates of >23 r/day[37] (Figure 4). Assuming that this damage occurred during the first six months of exposure, the total exposure required to kill them was about 4100 r. Laboratory experiments with seedlings have shown that >90% mortality occurs commonly in *Pinus rigida* at acute exposures in the range of 500 to 1000 r. Occasionally seedlings survive as much as 2000 r. Assuming that an acute exposure of 2000 r is the maximum that *P. rigida* will survive, there is then a ratio of about 2 between the total exposure administered chronically in the field over six months and the acute exposure needed to produce the same effects. The use of a factor of 2 therefore has been adopted for adjusting total six-month chronic exposures to the exposure from fallout.

EFFECT OF SEASON ON DAMAGE FROM FALLOUT EXPOSURES

The nature and severity of radiation effects are also influenced importantly by the phenological condition of the organisms irradiated. Dormant plants, for instance, are substantially more resistant to acute exposures and probably to fallout exposures than actively growing plants (Figure 7). This difference spans a factor of 2, possibly more. The variation in sensitivity during the entire life cycle in plants is even greater[29] and it is still greater in insects.[10] From the standpoint of damage to the plant populations that dominate the structure of terrestrial ecosystems, the greatest sensitivity to fallout radiation would be in the spring or early summer, the least probably in late summer or fall, when there would be a maximum period for recovery before the next growing season. The range of variation in somatic effects introduced would span a factor of at least 2, possibly more. Where effects on sexual reproduction or seed set are important, as they would be in many agricultural or horticultural plants, the variability would be potentially much greater, with certain stages probably sensitive to as little as one-tenth the exposure necessary to affect vegetative growth adversely.

PATTERNS OF RADIOSENSITIVITY AMONG ECOSYSTEMS

It has been suggested by Woodwell[35] that there are patterns of radiosensitivity among ecosystems. He based this conclusion on several relationships. First, a striking difference has been observed between the exposure necessary to devastate the forest and that to alter the old field. Second, there are sharp differences in sensitivity between such trees as pines and oaks, both of which are important dominants of different ecosystems. Third, the gymnosperms in general, which form the major component of certain ecosystems in both the Northern and Southern Hemispheres, have been shown in several studies to be more sensitive than the majority of angiosperms to damage from ionizing radiation. This is particularly evident in Figure 8, which shows that gymnosperms in general have larger chromosome volumes than angiosperms

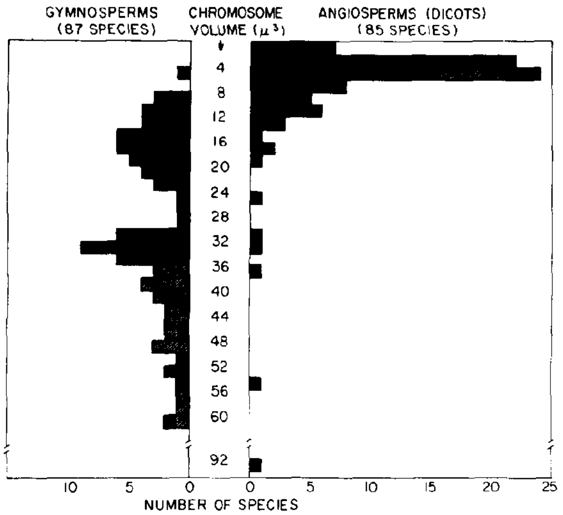

Figure 8. Comparison of the distribution of interphase chromosome volumes of 172 species of dicotyledonous and gymnospermous plants (adapted from Sparrow[23]).

and therefore are probably more sensitive to radiation. Fourth, certain adaptations such as the annual habit, asexual reproduction, and high degrees of polyploidy are characteristic of plants of certain types of ecosystems (see Sparrow and Woodwell[29] for further discussion). These adaptations contribute importantly to resistance to radiation damage as well as to ability to survive harsh environmental conditions. Among successional ecosystems, the early stages characterized by herbaceous annuals are substantially more resistant than the later forest stages, the difference spanning a factor of 5 to 10 in the Eastern Deciduous Forests (Figures 5 and 6).

DISCUSSION OF THE SEVERITY OF FALLOUT RADIATION EFFECTS ON NATURAL ECOSYSTEMS

Most natural ecosystems of temperate zones retain their capacity for regenerating the climax after a wide range of types and degrees of damage. Forests are usually self-regenerating units, even after clear cutting; abandoned fields revert to stable native vegetations through a series of developmental stages. It is axiomatic that these successions are not regressive but developmental, leading toward climax.[6] The physical destruction initiating the succession causes the regression and, if the destructive influences are chronic, may maintain one of these developmental stages indefinitely as a Clementsian subclimax or disclimax. Destruction of the ecosystem, however, may reduce the potential of the site for supporting life for long periods, possibly for scores of years, at least in the diversity present previously. This would be true, for instance, if erosion occurred or if there were a loss of essential nutrients which had accumulated in the system through hundreds of years.

Three categories of damage to natural ecosystems which might be caused by ionizing radiation are discussed below. The first two include damage whose repair is well within the capacity of the system. The third category includes severe effects which might lead to a long-lasting reduction in the capacity of the habitat to support an ecosystem equivalent in complexity to the one destroyed.

Minor Effects

Low exposures may inhibit growth of sensitive species temporarily, possibly reducing reproductive capacity as well. Such minor effects are common in nature from various causes such as wind or frost or unfavorable seasons, and the impact of radiation-induced effects would be similar to these. Recovery from such damage occurs rapidly without changes in the species composition of the plant community and without conspicuous change in the direction or rate of succession. Damage of this nature would be considered "minor." The exposure required to produce this "minor" effect would vary in different ecosystems (see Table 2).

Intermediate Effects

Selective inhibition or mortality of sensitive populations would initiate successions similar to those following catastrophic storms, grazing, or selective logging of forests. The generalized pattern would involve the immediate direct effects of the radiation followed by shifts in both the plant and animal populations to occupy the new resources available. These shifts are part of the homeostatic processes characteristic of natural ecosystems and usually, although certainly not always, proceed in orderly and grossly predictable fashion, without catastrophic insect or plant plagues. Included in this category is damage that is severe enough to change the populations of plants present and thereby initiate new successions.

The conditions under which the initial damage caused by the radiation would be amplified by biological interactions before the establishment of an orderly succession are largely unknown and highly speculative and probably depend primarily upon the severity of the radiation damage. The principal type of interaction possible would seem to involve secondary damage to plants from herbivorous insects which are capable of relatively rapid reproduction. Such interactions have been observed in the Irradiated Forest Experiment at Brookhaven, but effects have been short-lived and the damage has been minor. The possibility of rapid upsurges of plant pathogens cannot be disregarded, although evidence for it is so far lacking. These biological interactions might be expected within this category of effects, especially at higher exposures, but would not prevent the establishment within 2 to 3 years of an orderly succession leading toward an ecosystem basically similar in structure and function to the system destroyed.

Severe Effects

Very intense exposures of ecological systems to ionizing radiation might damage them sufficiently to reduce the capacity of the site for supporting life, slowing the succession greatly or diverting it toward a new, less complex climax. There are certain parallels for this type of destruction. The harvest or burning of certain tropical rain forests for instance is thought to lead to the removal by leaching of essential

Table 1

Estimated Acute Exposures Required To Affect Dominants
of Major North American Vegetations

Estimates are based on correlations between radiosensitivity and interphase chromosome volume. Variability introduced into the estimates by the measurements of nuclear volumes alone is about ±30% of the means listed. Other uncontrolled intrinsic and environmental factors increase the potential errors greatly (see text). Data reported are those available in January 1964.

	Somatic chromosome number	Interphase chromosome volume (μ^3)±S.E.	Sensitivity range: slight inhibition of growth to mortality, r
	FORESTS		
Boreal			
Picea glauca	24	39.7±1.6	220- 590
Abies balsamea	24	33.4±2.2	270- 700
Subalpine (Rocky Mountains)			
Picea engelmannii	24	26.8±1.6	330- 880
Abies lasciocarpa	24*	33.5±1.7	270- 700
Montane (Rocky Mountains)			
Pseudotsuga menziesii	26	28.5±1.1	310- 820
Pinus ponderosa	24	36.7±2.8	240- 640
Montane (Sierra-Cascades)			
Abies concolor	24	23.3±0.9	380- 1010
Pinus lambertiana	24	57.8±3.1	150- 410
P. jeffreyi	24	48.1±1.9	190- 490
P. ponderosa	24	36.7±2.8	240- 640
Pseudotsuga menziesii	26	28.5±1.1	310- 820
Pacific Conifer			
Tsuga heterophylla	24*	23.7±0.9	377- 990
Thuja plicata	22	8.6±0.4	1040- 2730
Abies grandis	24	33.2±1.1	270- 710
Eastern Deciduous			
Mixed Mesophytic			
Fagus grandifolia	24	2.3±0.1	3810-10000
Magnolia acuminata	76	4.8±0.2	1850- 4840
Tilia americana	82	2.5±0.1	3520- 9230
Liriodendron tulipifera	38	6.4±0.5	1400- 3680
Acer saccharum	26	3.2±0.2	2800- 7360
Quercus alba	24	6.6±0.3	1350- 3550
Tsuga canadensis	24	21.3±0.8	420- 1100
Beech-Maple & Maple-Basswood			
Fagus grandifolia	24	2.3±0.1	3810-10000
Acer saccharum	26	3.2±0.2	2800- 7360
Tilia americana	82	2.5±0.1	3520- 9230
Hemlock-Hardwoods			
Tsuga canadensis	24	21.3±0.8	420- 1100
Betula lutea	84	2.2±0.1	3860-10120
Pinus strobus	24	46.5±2.8	190- 500
P. resinosa	24	43.2±3.5	210- 540
Acer saccharum	26	3.2±0.2	2800- 7360

Table 1 (continued)

Eastern Deciduous (continued)			
Oak-Chestnut			
Castanea dentata	24	4.7±0.3	1900- 5000
Quercus coccinea	24	3.6±0.3	2490- 6530
Q. prinus	24	6.1±0.3	1470- 3870
Pinus rigida	24	48.3±2.8	190- 490
Oak-Hickory			
Quercus alba	24	6.6±0.3	1350- 3550
Q. rubra	24	5.5±0.3	1620- 4250
Q. velutina	24	3.2±0.2	2830- 7430
Q. stellata	24	4.4±0.2	2040- 5350
Q. marilandica	24	3.3±0.2	2690- 7060
Carya ovata	32	2.5±0.2	3560- 9340
C. cordiformis	32	1.8±0.1	5090-13370
C. tomentosa	64	1.8±0.5	5080-13350
C. laciniosa	32	2.6±0.1	3470- 9110
Pinus taeda	24	52.6±4.1	170- 450
	GRASSLANDS		
Andropogon scoparius	40	6.4±0.4	2330- 9200
	AGRICULTURE		
Zea mays HV Golden Bantam	20	14.0±0.6	1060- 4200
Tetraploid	40	10.8±0.6	1370- 5410
Triticum aestivum	42	14.6±1.1	1020- 4020

*Probable chromosome number.

nutrients normally held in the system and recycled. The loss of these nutrients following destruction of the forest limits the rate of succession and may delay indefinitely the re-establishment of the original vegetation. Erosion following logging or fires on steep slopes in temperate regions may have similar effects through loss of nutrients compounded by the presence of unstable soils. If destruction were severe over many square miles, seed sources might be remote from devastated areas, which would further slow rates of succession and possibly alter the potential of the site for developing the original climax. Climatic changes, which isolated seed sources, seem to have caused the grassland and heath-shrub areas called "balds" in the Southern Appalachians.[14,32]

It is possible at present to estimate in general terms the radiation exposures necessary to produce these broad categories of effects. Such a prediction can be based on (a) the correlation between radiosensitivity and interphase chromosome volume, and (b) the limited experience we have had with irradiated natural ecosystems. This correlation has been used to predict the potential effects of acute radiation exposure of major dominants of certain natural vegetations in North America (Table 1). Exposures listed are average exposures required to cause damage in plants ranging from slight inhibition of growth to mortality of all individuals. Variability in the measurements of chromosome volumes and in the data used in the regression equation introduces errors which place the 95% confidence limits ≈30% above and below the exposures listed. Other intrinsic and environmental factors influencing radiosensitivity of plants in nature have not been accounted for in these estimates and could introduce variability of as much as five times the means under field conditions.[37]

Estimates of radiosensitivity of species for which data were available in January 1964 are given in Table 1. Terminology of the vegetation follows Oosting.[18] Plant names follow Little[12] where Fernald[8] does not apply. Species that are dominant in more than one vegetation are repeated to simplify use of the table.

Average interphase chromosome volumes range from highs of about 50 μ^3 for certain of the pines to lows of about 2 μ^3 for some of the hickories. The gymnosperms in general have much higher chromosome volumes than the angiospermous trees, although *Thuja plicata* appears to be an exception, having an average chromosome volume of 8.6 μ^3, which is much closer to the 6.6 of white oak than to the 48.3 of pitch pine.

Estimated acute exposures to kill 100% of any population range from lows of about 500 r for certain pines through highs of 10,000 to 13,000 r for birch, beech, and the hickories. In general, the forests that contain gymnosperms as major dominants appear to be more sensitive than the deciduous forests of the East. Exposures of a few hundred to 2000 r are enough to kill most trees of the coniferous forests, while 5 times that exposure range would be required to do the same damage in hardwood forests.

Few data were available for native grasslands. *Andropogon scoparius*, the broom sedge, has an average interphase chromosome volume of 6.4 μ^3, which suggests that it would be killed by exposures of $<$10,000 r.

Corn and wheat have larger chromosome volumes, 14 and 14.6 μ^3, respectively. According to the correlation, exposures of $<$5,000 r would kill both plants.

Extension of such predictions as these to anticipation of effects on ecosystems is subject to large errors. There is no question, however, that radiation exposures in the range 10,000 to 100,000 r will kill all or most of the higher plants of certain ecosystems. The capacity of the systems for recovery depends on a host of factors including the availability, distribution, and vitality of seeds; the ability of surviving plants to sprout or produce seeds; the numbers of destructive insects which survive or which, living nearby, can infiltrate and multiply; the uniformity of the fallout distribution; the size of the area devastated and its condition (whether burned or not); and the environmental conditions during and after exposure.

Probably the most important single factor that might delay recovery indefinitely in North America would be unstable soils. Montane and piedmont areas would be particularly sensitive to erosion and to radiation damage, since the principal trees of many of these areas are the highly sensitive gymnosperms. Deciduous forests in lowlands would be substantially less sensitive, probably by as much as an order of magnitude, because the trees themselves are less sensitive to radiation damage, there is a greater diversity of species available to contribute to stabilization of the site and recovery of the system, and there is less possibility of severe erosion.

Destruction of vegetation over areas as large as tens or hundreds of square miles might slow recovery by isolating devastated areas by distance alone from sources

Table 2

Estimated Radiation Exposures Required To Damage Major Ecosystems

Major ecosystems	Level of Damage Minor	Intermediate	Severe
City	200	200	—
Agriculture	200	200	—
Coniferous forest	200	200- 2000	>2000
Deciduous forest	200	200-10000	>10000
Grassland	2000	2000-20000	>20000
Herbaceous successional	4000	4000-70000	>70000

of recolonization. The probability that destruction could be that severe after a heavy attack is real enough.[16] Fire might follow such widespread devastation, slowing recovery further.[4]

Table 2 summarizes the radiation exposures estimated as necessary to produce the three levels of effects in North American ecosystems. Estimates are based on the field studies summarized in this paper, on data from the literature, and on the correlations reported between radiation tolerance and nuclear or chromosomal volumes. All such estimates are subject to large errors at present, but it is useful to make a broad appraisal of radiation exposures necessary to cause varying degrees of damage to major ecosystems.

In cities and most agricultural ecosystems the most sensitive dominant organism is man, and the severity of radiation effects on the system would be determined by his ability to survive and function normally. If radiation exposure is the only hazard, serious effects would be apparent in men at exposures >200 r.[30] Few, if any, people would survive whole-body exposures >1000 r of gamma radiation.

In ecosystems not dominated by man, the greatest changes in structure would follow damage to the plant populations. The sensitivities of these populations range from those of the gymnosperms, some of which may be killed by exposures in the same range that kills man (500 to 1000 r), to those of the highly resistant forms such as certain algae and fungi whose tolerances go above 100,000 r. In these ecosystems the net effect of the radiation would be simplification of the system by selective inhibition or mortality of sensitive species. Although mammals and even certain stages of insects[10] might be substantially more sensitive than most of the plant populations, the major changes in the structure and function of natural ecosystems would probably be associated with the direct effects on the plants and with the plant successions initiated.

Table 2 shows that intermediate effects, including the initiation of new successions, would be expected in coniferous forests at exposures in the range of a few hundred to about 2000 r. The upper limit for such effects extends to about 10,000 r in deciduous forests and to 20,000 r and above in grasslands and communities of herbaceous plants. At exposures above these, radiation damage would be severe by our definition, probably beyond the limits of homeostasis for certain ecosystems, especially those in which erosion may occur. Although these estimates are tenuous, it would seem wise to bend future research efforts less toward refining their precision than toward eliminating the hazard of catastrophic irradiation.

SUMMARY

1. The purpose of this paper is to define broadly the potential effects of fallout radiation on the natural ecological systems forming the homeostatic matrix within which civilization exists.

2. Ecosystems have three basic patterns: geographic pattern, such as deserts, grasslands, forests, and tundras; temporal patterns which are successions; and patterns of internal structure and function. The latter can be defined in many ways. In this paper the distribution and flow of energy among the various populations is used.

3. Three sources of information are available for analysis of the potential effects of fallout radiation on these patterns: data from experimentally irradiated ecosystems, data from radiobiological studies of many organisms, and data from other parallel catastrophes in which ionizing radiation was not a factor. This discussion concentrates on the first two sources.

4. Experimentally irradiated ecosystems contributing data to this analysis include those around the Lockheed reactor in northern Georgia and recent experiments in an oak-pine forest and in old fields at Brookhaven National Laboratory.

5. Radiobiological data of particular use are the correlations recently developed at Brookhaven between the radiosensitivity of plants and chromosome volume.

6. These analyses show patterns of radiosensitivity among the plant populations of natural ecosystems; communities of herbaceous annuals, for instance, would probably withstand fallout radiation exposures up to 4000 r with minor effects, while most coniferous forests would be devastated by 2000 r or less.

7. Field experiments with small, open, irradiated ecosystems have shown no clear tendency for devastating population explosions of insects after radiation damage, but experience is limited. Changes in herbivorous insect populations have followed, in general, the abundance of food.

8. Three categories of radiation effects on ecosystems were established for predicting potential fallout effects: minor effects involving temporary inhibition of growth or reduction of reproductive capacity in plants, intermediate effects involving the initiation of new plant successions, and severe effects involving the potential alteration of the capacity of the site to support life. This latter range of effects might occur after erosion or loss of essential nutrients. Prediction of "severe effects" is subject to large uncertainties introduced by ecological factors in addition to irradiation.

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EFFECTS OF CHRONIC GAMMA IRRADIATION ON PLANT COMMUNITIES

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ABSTRACT

Three plant communities or assemblages of plants — the vascular plants of an oak-pine forest, the lichens of that forest, and herbs of an old field — have been studied after being exposed experimentally to chronic gamma irradiation. Several kinds of changes in the communities have resulted, including: (1) in all three communities irradiation reduced community structure toward the lowest strata or growth-forms of the community; (2) dominant species replaced one another along the gradient of radiation intensity producing population curves similar to those found along natural environmental gradients; (3) significant changes in productivity occurred; (4) species-diversity decreased with increased exposure to radiation; (5) in respect to various tests used in the study, increasing community sensitivity to irradiation was in the sequence: forest lichens, old-field herbs, forest vascular plants. Radiation effects on communities relate to evolutionary and ecological phenomena of broad interest, including nuclear volume effects on radiation sensitivity, stature and evolutionary level of plants, population processes determining community composition, and relations of communities to succession and natural environmental gradients.

INTRODUCTION

EXPOSURE to ionizing radiation at intensities much above the background from natural radioactive decay and cosmic rays is a new problem in biology. It has arisen because of the use of atomic energy in both war and peace, a use that has been accelerating for the past quarter century and holds almost incomprehensible potential for both benevolence and destruction. The need to know the consequences of exposure to ionizing radiation is real; no less real is the interest inherent in understanding the effects of a factor which, while "unnatural" at intensities far above background, has been present throughout the evolution of life and has fundamental effects on heredity. The effects occur, of course, at all levels of integration in living systems, ranging from the molecular through ecological levels.

The effects of ionizing radiation on plants have been studied extensively (Sparrow, Binnington and Pond, 1958; Sparrow, 1960, 1961; Gunckle and Sparrow, 1961; Schultz and Klement, 1963; Sparrow, Sparrow, Thompson, and Schairer, 1965; Hungate, 1966). Some of the generalized conclusions are; (1) that damage from irradiation involves production of mutations (Muller, 1927), using "mutations" in its broadest context to include gross and subtle changes in chromosomes; (2) that the most sensitive tissues are meristematic (Bergonie and Tribondeau, 1906); (3) that there is great variation among species in sensitivity to radiation (Odum, 1959; Sparrow and Woodwell, 1962); and (4) that sensitivity is related to characteristics of the nucleus, especially to the average volume of chromosomes (Epstein, 1953; Terzi, 1961, 1965; Sparrow, Underbrink and Sparrow, 1967).

Information specific to community-level effects is beginning to accumulate from studies at bomb test sites (Fosberg, 1959a, 1959b; Palumbo, 1962; Beatley, 1965a, 1965b, 1966;

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Shields and Wells, 1962, 1963; Martin, 1963), around reactors (Platt, 1963, 1965; Witherspoon, 1965; Witkamp, 1961), gamma sources (McCormick, 1963), and from more recent experiments at Oak Ridge National Laboratory (Taylor, 1966), Savannah River (Monk, 1966; McCormick and Golley, 1966), Puerto Rico (Odum, 1965), Brookhaven National Laboratory (Woodwell, 1962, 1967; Woodwell and Sparrow, 1965; Woodwell and Rebuck, 1967), and elsewhere. The studies reveal that interest in radiation effects on communities goes far beyond simple observation of damage and that effects are related to various other basic ecological phenomena. This summary is offered to focus attention on some of the broader biological questions raised by work to date on the ecological effects of ionizing radiation.

COMMUNITIES STUDIED

Responses to irradiation have been studied at Brookhaven National Laboratory in four types of plant communities: a forest, an abandoned field, and in the shrub and lichen communities of the forest. The forest is an oak-pine stand such as described by Conrad (1935), and is dominated by white oak (*Quercus alba*), scarlet oak (*Q. coccinea*) and pitch pine (*Pincus rigida*). [Nomenclature of higher plants follows Fernald, 1950.] There is a high coverage of vacciniaceous shrubs (*Gaylussacia baccata, Vaccinium vacillans* and *V. angustifolium*), and a sparse herb stratum (about 1 per cent cover) with *Carex pensylvanica, Gaultheria procumbens, Pteridium aquilinum* and other species (Woodwell and Rebuck, 1967). In the abandoned field the response of communities of herbaceous plants to irradiation was observed. These communities had developed through one and two years following abandonment from agriculture. The shrub and lichen subcommunities, or synusiae, of the oak-pine forest merit separate treatment because of the difference in their responses from those of the trees (Reiners, 1965; Brayton and Woodwell, 1966; Woodwell and Gannutz, 1967). All these communities occur on the sandy, glacial outwash soils of nearly level terrain in central Long Island. Forests of this area have been subject to fire; the experimental forest was burned, probably about 1918. Although not a climax community, the forest is late successional or near-climax on these soils (Whittaker and Woodwell, 1967); "climax" is used, not in the sense of a single, climatically determined end-point of successions, but rather, in the sense of a community in steady-state in relation to its own environment (Whittaker, 1953). Study of both forest and field allows comparison of responses to irradiation in the unstable, pioneer assemblages of herbs and the more stable, late-successional forest.

The communities were exposed to chronic irradiation by gamma sources that produced approximately equivalent radiation fields. Irradiation of the forest was started in November, 1961; the herbaceous communities were allowed to develop during 1961–63 in sectors of the Gamma Radiation Field established a decade earlier at Brookhaven. Irradiation of the forest was with 9500 Ci of ^{137}Cs; that of the field with 3000–4000 Ci ^{60}Co. Both sources were shielded four hours daily to permit access to the vegetation. Details of the techniques and equipment of the experiments have been given by Woodwell (1963), Sparrow (1966), and Woodwell and Oosting (1965). The field has been observed through two years and the forest through five years of exposure to radiation, which was continuous except for the daily periods when the sources were shielded.

Intensity of radiation decreases with the square of distance from such sources, with minor exceptions because of absorption and backscatter (Cowan and Meinhold, 1962; Cowan and Platt, 1963). Trunks of trees produce significant shielding, revealed in the forest by green "shadows" of living *Carex* in a zone where most other vascular plants were killed. The reduction in exposure is roughly 5 per cent per cm of woody tissue. Thus a 10 cm tree would make a "shadow" where the minimum exposure was one-half that in front of the tree (Woodwell, 1963; Woodwell and Rebuck, 1967). Because of this variation in the radiation field, detailed biological studies have been based on the average exposures at any distance, derived from a study of the frequency distribution of exposures in the forest (Woodwell and Rebuck, 1967). The research was designed as an experiment comparing responses of communities along the gradient of intensity of radiation from background (in control areas remote from the source) to the very high, commonly lethal levels within a few meters of the source. The approach is thus gradient analysis — the study of relationships of gradients of species populations and the characteristics of natural communities on the one hand to environmental gradients on the other (Whittaker, 1967) — applied to the "unnatural" environmental gradient of radiation intensity. Responses of communities to this gradient will be discussed as five types of effects: effects on physiognomy, on populations of species of plants, on production, on diversity, and on community composition measured as "relative similarity."

THE ECOLOGICAL EFFECTS OF RADIATION

Effects on Physiognomy

Effects of irradiation on the physiognomy (or structure) of communities are best generalized in a transect diagram of a forest (Fig. 1, cf. Woodwell, 1967, Fig. 12). Zones of disturbance have been classified as follows (Woodwell and Rebuck, 1967): (1) Devastated Zone, the inner zone receiving more than 200 R/day, where all woody and most herbaceous plants were killed during the first year of the experiment; (2) *Carex* Zone, where all woody plants were killed and the sedge *Carex pensylvanica* expanded its populations in two years to cover as much as 50 per cent of the ground surface in certain areas (the expansion occurred in areas receiving average exposures of between 200 and 150 R/day in 1962, although the limits of all such zones must be drawn somewhat arbitrarily); (3) Shrub Zone (40–150 R/day in 1962), a "heath" where the tree canopy had been reduced to 50 per cent or less of its normal canopy cover, and where the vacciniaceous shrubs were the dominant plants; (4) Oak Forest (16–40 R/day in 1962), in which pitch pine had been killed leaving an oak canopy and undisturbed undergrowth (although the oaks were living, bud and twig development, and amount and timing of leaf fall were affected (Woodwell and Rebuck, 1967; cf. McGinnis, 1963); (5) Oak-pine Forest, at exposures less than 12 R/day in 1962 (7 R/day in 1963, 4.2 R/day in 1964), where no mortality of plants was observed, although there was appreciable reduction of shoot growth at exposures as low as 1 R/day (Woodwell and Sparrow, 1963).

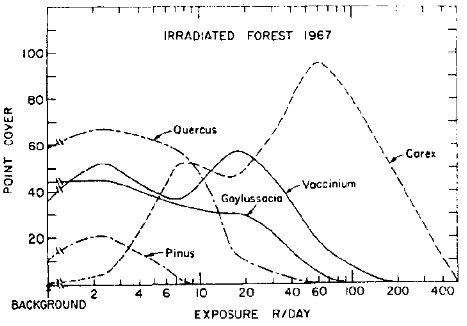

FIG. 1. EFFECTS OF CHRONIC IRRADIATION ON THE PHYSIOGNOMY OF A FOREST

At the highest exposures all the higher plants were killed, leaving only mosses and lichens. At progressively lower exposures herbs, shrubs, and trees survived and even expanded their populations in a sequence parallel to that observed along gradients of decreasing severity of climate as in the transition from tundra to forest.

This sequence of life-forms — lichens and mosses, herbs, shrubs, trees — is familiar, for it appears in many successions. It appears also, with perhaps more striking parallelism to the effects of irradiation, in the gradient of vegetation on mountains from the lichen and moss communities of highest altitudes, through sedge meadow and ericaceous shrub communities, to forests at lower elevations (Woodwell, 1967). The latter gradient is an example of the well-known generalization that stature of dominant plants, community coverage, and differentiation into strata tend to increase with progression toward more favorable environments, and to decrease toward more severe environments (Dansereau, 1951; Whittaker, 1954, and others). The response of the forest to irradiation conforms to this generalization, with reduction of stature of dominants, total coverage, and stratal complexity toward more severe exposure to irradiation.

The pattern appears not only for the forest as a whole, but within its shrub community. Among the shrub species, *Gaylussacia baccata* is more sensitive than *Vaccinium vacillans*, which in turn is more sensitive than *V. angustifolium* and the sedge *Carex pensylvanica* (Brayton and Woodwell, 1966). The sequence is one of decreasing stature from *Gaylussacia* (about 0.5 m mean height) through the two *Vaccinium species* (0.25 m and 0.10 m) to *Carex* (less than 0.1 m). Other unexpected physiognomic trends in response to irradiation appear in the old-field and lichen communities. The first-year old-field communities consist of herbs of which, in the control samples, 85 per cent of the species are erect and 15 per cent prostrate (including decumbent or geniculate according to Fernald, 1950). The proportion of prostrate species rises to 50 per cent at about 100 R/day, and to 100 per cent at about 2000 R/day (Woodwell, 1967). In the lichen synusia the numbers of both fruticose and foliose species decline until, at about 2000 R/day, only the crustose species remain (Woodwell and Gannutz, 1967).

Patterns of survival in all four communities or subcommunities thus show increasing disadvantage of erect stature with increasing exposure to radiation. Since the sources of irradiation were above ground, the effect is not one of ground-surface shielding. Effects on dose from shielding by tree trunks and from backscatter are largely averaged out by considering populations at different distances from the source, rather than by considering individual plants. At a given distance from the source mean radiation exposure should be nearly equal for tissues of *Quercus*, *Vaccinium* and *Carex*, and for tissues of foliose and crustose lichens. Despite differences in radiation sensitivity of species of a given growth-form, there appears to be significant correlation of radiation sensitivity with growth-form. It is this correlation that underlies the physiognomic responses of communities to ionizing radiation.

Effects on Populations of Species

Changing balances among species populations, including replacement of dominant species, have been observed in natural communities exposed to different intensities of irradiation (Auerbach, 1958; Woodwell, 1962, 1967; McCormick, 1963; Daniel, 1963). In the Brookhaven experiments irradiation both reduced populations of some species, and permitted compensatory expansion in the populations of other ones. The most conspicuous changes in abundance in the forest involved inverse relationships between coverage of trees and shrubs and of the sedge, *Carex pensylvanica* (Fig. 1). As cover of trees and shrubs declined the cover of *Carex* increased from less than 1 per cent in the undisturbed forest to more than 50 per cent in certain areas at high radiation exposures. A similar but less striking replacement of dominance occurred in the shrub community when density (as distinguished from the somewhat less sensitive index, coverage) was considered. As the tree canopy was reduced at increasing radiation exposures there was an increase in the density of *Gaylussacia*. An inverse relation of *Gaylussacia* to tree cover was observed also in unirradiated forests by Reiners (1967). At higher radiation exposures, *Gaylussacia* densities declined while *Vaccinium vacillans* increased slightly; at still higher exposures, *V. vacillans* declined while *V. angustifolium* increased. As all of the shrubs were excluded by still higher exposures, the *Carex* replaced them as the dominant plant and was itself replaced close to the source by *Cladonia cristatella* and other lichens (Woodwell and Rebuck, 1967; Brayton and Woodwell, 1966; Woodwell and Gannutz, 1967).

Harvest of the standing crop of first-year old-field herbs along the gradient of radiation also showed shifts in the abundance of species (Woodwell and Oosting, 1965; Woodwell, 1967). The most important changes were: (1) replacement of the dominance of *Chenopodium album* and *Erigeron canadensis* by *Digitaria* species. (2) Standing crops of populations along this gradient and the gradient of radiation in the forest showed peaked curves (Woodwell, 1967, Fig. 3; cf. McCormick, 1963) resembling binomial distributions, the form suggested for populations along natural environmental gradients (Gause, 1930; Whittaker, 1951, 1952; Brown and Curtis, 1962). (3) These distributions are symmetrical only in relation to the logarithm of radiation intensity; they are strongly skewed along a linear gradient of radiation intensity. The relation to the logarithmic gradient suggests that (in analogy with the Weber-Fechner law) the effect of increase in radiation exposure is proportional to $\Delta R/R$, the increase in relation to the radiation intensity beyond which the increase occurs. Similar responses of populations in relation to a logarithmic gradient of salinity in inland lakes were observed by Whittaker and Fairbanks (1958). (4) Although "zones" characterized by physiognomy or dominant species are convenient for description, the change in the importance of species and in community composition along the radiation gradient is continuous. In general, the manner in which importance values and community composition relate to the radiation gradient are consistent with those observed in continua of natural communities in relation to natural environmental gradients studied by Whittaker (1951, 1956, 1967), Curtis and McIntosh (1951) and others.

A further relation to disturbance and successional gradients may be illustrated for the principal species of shrubs in the forest. The species *Gaylussacia baccata, Vaccinium vacillans, V. angustifolium* and *Carex pensylvanica* form, as indicated, a sequence of dominance replacement with increasing exposure to radiation and also a sequence of decreasing plant height. The response of these species to frequency of fires (Buell and Cantlon, 1953) is generally parallel to their response to irradiation (Brayton and Woodwell, 1966). Full parallelism of species responses to radiation and fire exposure should not be expected. These parallels suggest, however, along with the physiognomic observations, that there is correlation of the tolerance of irradiation with tolerance of other environmental stresses, especially physical stresses, among different plant species and growth-forms (Woodwell, 1967).

Effects on Productivity

One usual effect of irradiation has been decreased net production, but this has not always been true. In the first-year old field, the end-of-season harvest (including roots) increased from 400 g/m^2/yr in the control community to 800 g/m^2/yr at 1000 R/day; beyond 1000 R/day production decreased to near zero at 2000 R/day (Woodwell and Oosting, 1965; Woodwell, 1967). The meaning of the increase in harvest up to 1000 R/day is uncertain but the contrast between the sets of samples seems statistically significant. The results suggest that the prostrate *Digitaria,* which has trivial production in communities in which it is shaded by erect herbs, is able, when released from shading, to use resources for short-range production more effectively than the erect herbs. In this case, irradiation results in replacement of an open herb community of moderate production by a mat of *Digitaria,* which has high production for a dry grassland. It seems clear that in this old-field community effects of radiation are expressed in changing composition without reduction in total productivity, up to levels of radiation (approaching 2000 R/day) which exclude even the most resistant of the community's species.

Above-ground net annual production of forest outside the irradiated area is estimated from unpublished data to be 846 g (dry weight) per m^2 (802 g/m^2 for trees, 42 g/m^2 for shrubs, and 2 g/m^2 for herbs); total above- and below-ground net annual production is estimated at 1124 g/m^2. The production is near, but lower than, the range of 1200–1400 g/m^2/yr observed for climax forests of more favorable environments (Whittaker, 1966). Exposure to more than 300 R/day for six months reduced production of the forest to very close to zero. Here virtually all of the indigenous higher plants were excluded. Production of trees was zero at exposures in excess of 150 R/day and was reduced substantially at exposures of 40 R/day. Within the five years of this study there was a modest increase in production of the more resistant undergrowth plants, which compensated only in part for the reduction of the tree production. In the zone exposed to 17–18 R/day (50–52 m), where the tree canopy had been reduced substantially after five years exposure, there was a 20 per cent increase in net production of the low-shrub stratum to 50 g/m^2/yr, above-ground. This was the maximum production of low shrubs along the gradient. The production of *Carex pensylvanica,* however, increased from about 2 g/m^2/yr to 100–200 g/m^2/yr in this zone and in areas receiving exposures up to 160 R/day. At higher exposures it dropped abruptly to zero. Although a few scattered herbs occurred at higher exposures (Wagner, 1966), combined production of these was less than 1 g/m^2. The contrast between the forest and old-field in productivity under irradiation is striking. In the more stable and highly organized forest, exposure over 6 months to 40 R/day destroyed the dominant species within one year and reduced production to less than one-half of that of the control. In the unstable and loosely organized old field increasing exposure up to 1000 R/day changed its composition without reducing production.

Part of the meaning of exposure to ionizing radiation for forest production involved effects on photosynthesis and respiration. Irradiation of pine trees during the winter reduced net photoysnthesis, probably due in part to an increase in rate of respiration and in part to a depression in the efficiency of photosynthesis (Bourdeau and Woodwell, 1964). Field and greenhouse studies of the effects of irradiation on photosynthesis and respiration show that there is a consistent general depression in the rate of net photosynthesis under chronic and acute irradiation (Hadley and Woodwell, 1965; Woodwell, unpublished). Dark respiration of leaves and respiration of stems follow less clearly defined patterns. Under chronic irradiation dark respiration of pine branches was stimulated, especially as the tree approached death under high chronic exposure (Bourdeau and Woodwell, 1964). After acute irradiation no change in the rates of dark respiration of branches could be detected in pine seedlings, although there was an immediate increase in the rate of respiration of the stem followed by a persistent depression (Hadley and Woodwell, 1965). Rates of decay of organic matter in soil and of litter were enhanced by irradiation at about 600 R/day, further supporting the conclusion that respiration rates are often enhanced by irradiation (Woodwell and Marples, 1967; Romani and Bowers, 1963; Kaman, Aharoni, and Lattar, 1965), although certainly not universally so (Woodstock and Justice, 1967; Bourdeau and Woodwell, 1964). The depression of photosynthesis and enhancement of respiration implies a decrease in net production due to direct effects of irradiation on metabolism. The mechanisms of these shifts in metabolism under irradiation have not been clearly defined.

These effects, however, are compounded under chronic irradiation, which partially defoliates the trees, reducing photosynthetic area without proportional reduction in the total amount of tissue respiring. The shift is most important in large perennial plants which have a larger investment in living support tissue in proportion to their photosynthetic tissue than smaller plants. Physiological and morphological effects of irradiation converge in these plants to make the balance of photosynthesis and respiration unfavorable. More broadly, the physiognomic trend of decreasing stature and stratal diversity of communities toward more severe environments may be based in part upon shifting balances between the advantage of plant height for light interception in favorable environments, and the disadvantage of erect woody structure and its respiratory requirements in less favorable environments that limit the amount of photosynthesis.

Effects on Diversity

The diversity of species of the oak-pine forest of Long Island averages 4.8 tree, 7.6 shrub, and 5.6 herb species per tenth-hectare plot; the total of 18 vascular plant species per plot is in a lower middle species-diversity range for a forest, and in the range of many mountain forests of high elevations (Whittaker, 1965; Whittaker and Niering, 1965). Plots smaller than 0.1 ha are needed to measure diversity along the radiation gradient; numbers of species in plots of different sizes appropriate to strata have been combined in a forest diversity index (Woodwell and Rebuck, 1967; Woodwell, 1967). Diversity thus expressed averaged 5.5 to 6.0 species in the unirradiated forest. Exposures of about 20 R/day (affecting *P. rigida*) caused a slight reduction in diversity in the first year of the experiment. At exposures above about 50 R/day diversity declined with a slope that was nearly linear in relation to the logarithm of radiation exposures. Diversity was reduced to one-half of the control at about 150 R/day in the 1962 samples, and to zero at 350 R/day (Fig. 2). There was a depression of the 50 per cent diversity point in the two subsequent years to about 90–95 R/day. Diversity of species in the old field showed no marked decrease at exposures up to 100 R/day or more; beyond these levels diversity decreased to zero at 3200 R/day. Diversity was reduced to 50 per cent

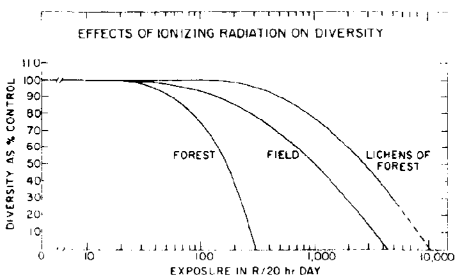

FIG. 2. CHANGES IN DIVERSITY OF PLANTS AFTER SIX MONTHS' CHRONIC GAMMA IRRADIATION, SHOWING THE GREATER RESISTANCE OF FIELD AND LICHEN COMMUNITIES

of the control at about 1000 R/day in the first-year old field.

Data on the diversity of the lichen populations in the first year of the experiment are incomplete. The threshold for reduction of diversity in the lichen community in the first year is believed, however, to have been 200–300 R/day, and reduction to 50 per cent diversity occurred at 2700 R/day (Woodwell and Gannutz, 1967). Some lichen species are highly resistant. Eleven species survived on trees at exposures of 2250 R/day after 32 months. A point of zero diversity could not be obtained, but the slope of the diversity curve suggests that this point should lie above 5000 R/day, possibly substantially higher.

Points of thereshold reduction of diversity, of 50 per cent reduction, and of reduction to zero for the three communities are thus all in the sequence — forest vascular plants, old-field herbs, and forest lichens. There are also differences in the relationship between diversity and production, and in the response to irradiation of the forest and old-field communities. Stratal differentiation, species-diversity, and production are poorly correlated with one another in general (Whittaker, 1965) and in detail along these gradients of radiation. Along the gradient in the forest, however, there was approximately parallel reduction of these three community characteristics with increasing exposure. The response of the community is in this case, within the period of observation, one of reduction and simplification without appearance of new species not present in the control forest. In the old field, in contrast, the response to irradiation involved (1) nonparallelism of the effects on production and diversity, (2) maintenance of full (or increased) production by communities of lower diversity with increased exposure up to 1000 R/day, a relationship similar to that along the salinity gradient in inland water bodies (Whittaker and Fairbanks, 1958), (3) addition to the flora at middle and higher radiation levels of species not present (or at least very rare) in the unirradiated old field.

Effects on Composition of Communities

Responses of the composition of communities to irradiation may also be expressed by such comparative indices as "coefficient of community" and "percentage similarity." Coefficient of community (Jaccard, 1902, 1912) is calculated as $CC = c/(a + b - c)$, in which c is the number of species shared by two community samples or floras, one of which includes a total number of species a and the other a total number of species b. Percentage similarity is calculated as $PS = 1 - .5\Sigma|a - b| = \Sigma\min$ (a, b), in which a is the percentage which one species comprises among the total number of individuals (or other relative measure of importance) in the first sample and b is the percentage which the same species comprises of the total in the second sample (Whittaker, 1952; Odum, 1950). Percentage similarity is usually computed by summing for all species the smaller of the two values of percentage representation for each species. A number of related measurements have been used by other authors (Dagnelie, 1960; Bray and Curtis, 1957; Greig-Smith, 1964; Whittaker, 1967). Coefficient of community expresses the relative similarities of two samples in terms of floristic composition; percentage similarity expresses relative similarity in terms of quantitative composition, with strong influence by the proportions of dominant species in the samples. Since they are different expressions of community response to environment, there is often advantage in using both, especially for a study of communities from contrasting environments (Whittaker and Fairbanks, 1958; Whittaker, 1960; Woodwell and Oosting, 1965).

The responses of the three communities —

forest, old field and the lichens of the forest — were similar in that a logarithmic increase in intensity of exposure produced an approximately linear reduction in coefficient of community (of samples from irradiated communities compared with controls). The similarity of the coefficient of community curve to the diversity curve was conspicuous in the forest, where there was little invasion of species not originally present in the undisturbed stand. Percentage similarity proved less useful for comparisons of communities along the radiation gradient, especially in the herbaceous field where changes in densities of species occurred irregularly, apparently in response to shifts in competitive relations (Woodwell, 1967).

Zero values for community similarity occurred at about 350 R/day in the forest vascular plants (for the first year of exposure), 1100 R/day in the second-year old field, and (by extrapolation) possibly 9000–10,000 R/day in the lichen community. When resistant species not present in the control are present at the higher radiation intensities, these values differ from values for zero species-diversity. Zero similarity is consequently more nearly an expression of the radiation sensitivity of the original community, as represented in the control sample, than is zero diversity. Both these zero values may be strongly influenced by a single, most resistant species. A 50 per cent reduction in community similarity provides a measurement more nearly expressing the sensitivity of the whole community to radiation. It should also be observed, however, that two replicate samples from the control community will give similarity values ("internal association" — Whittaker, 1952; cf. Bray and Curtis, 1957) of less than 100 per cent, and often they will be in the range of 60 to 80 per cent. The appropriate expression of community response is consequently reduction of similarity value to 50 per cent of that for replicated control samples; the measurement is one of a "half-change" in community composition (Whittaker, 1960; Whittaker and Niering, 1965) as a unit of ecological distance.

Radiation intensities to produce half-change in coefficient of community were 120 R/day for the forest vascular plants in 1962 (after 6 months' exposure), about 200 R/day for the second-year old field, and 1500 R/day for the forest lichens. These measurements, and reduction to 50 per cent of species-diversity of the control, are both possible expressions of community radiation sensitivity analogous to the LD_{50} as an expression of radiation sensitivity of populations. The two community measurements are necessarily correlated but, because of differences in species responses, they are loosely correlated. Fifty per cent diversity, like zero diversity, may be influenced by occurrence of species not present in the control samples: the half-changes in community similarity are more directly expressive of the sensitivity of the control community. Of the two half-change measurements (using coefficient of community or percentage similarity), coefficient of community is the more stable and less affected by population irregularity. CC_{50}, reduction of coefficient of community to half that of replicated unirradiated samples, consequently represents the authors' preference as an expression of relative sensitivity of communities to irradiation.

Relationship to Cellular Characteristics of Species

Damage from ionizing radiation is widely recognized to have its basis in phenomena on the cellular level, and much effort has been devoted to discovery of the principal site of damage (Lea, 1962; Bond, Fliedner, and Archambeau, 1965; Bacq and Alexander, 1961). There is wide agreement that the chromosomes are the primary targets and that the larger this target the more energy is absorbed from a given flux of radiation (Terzi, 1961, 1965; Sparrow, Sparrow, Thompson, and Schairer, 1965). This means that the sensitivity to radiation is correlated with volume of the chromosomes, a relationship which has been examined in detail for plants by A. H. Sparrow and his colleagues at Brookhaven National Laboratory and by others (Bowen, 1962; Evans and Sparrow, 1961; Miller and Sparrow, 1964; Sparrow, 1961, 1962, 1965; Sparrow and Miksche, 1961; Sparrow, Schairer, and Sparrow, 1963; Sparrow, et al., 1965; Sparrow, Underbrink, and Sparrow 1967; Yamakawa and Sparrow, 1965, 1966). The correlation has important implications at cellular and molecular levels; but, more important for us, it has been used successfully to predict radiosensitivity of organisms under experimental conditions from chromosome volume alone (Sparrow and Evans, 1961). With somewhat less accuracy it can be applied in attempts to predict ecological effects of radiation in the field.

Volume of the nucleus of meristematic cells as described by Sparrow and Miksche (1961) was used to predict effects of the first year's exposure of the Brookhaven Forest (Sparrow and Woodwell, 1962). All species involved in the prediction had chromosome numbers of $2n = 24$ (Woodwell and Sparrow, 1963), eliminating chromosome number as a variable. The prediction was largely correct in implying that trees would be the most sensitive species of the forest, and pitch pine (*P. rigida*) the most sensitive tree species. The high sensitivity of pitch pine at Brookhaven is consistent with that of loblolly pine (*P. taeda*) and other pine species, compared with deciduous trees in Georgia (Platt, 1963; Pedigo, 1963). All tree species at Brookhaven were, however, more sensitive than anticipated; and the relative sensitivities of different species varied from the prediction. Scarlet oak (*Q. coccinea*), expected to be the most resistant of the trees, was more sensitive to the first year's exposure than white oak (*Q. alba*). In later years under chronic exposure relative sensitivities shifted with the scarlet oak becoming more resistant than the white in accordance with the prediction (Woodwell and Rebuck, 1967; Woodwell and Marples, 1967). The pattern was complicated by sudden mortality in the scarlet oaks in these latter years, apparently from unexplained secondary effects of irradiation.

The shrubs of the forest were also more sensitive than anticipated and, as with the trees, relative sensitivities of different species varied from the predicted pattern. Growth of shrubs was inhibited by approximately 1/10 the exposure predicted and mortality occurred at about 1/5 the exposure predicted. The huckleberry (*Gaylussacia baccaia*) was predicted to be the most resistant of the shrubs; it proved instead to be the most sensitive (Woodwell and Sparrow, 1963; Brayton and Woodwell, 1966).

Nevertheless, the significance of the average volume of the chromosomes in determining the ecological effects of radiation becomes apparent when the exposures to inhibit growth by 90 per cent are plotted against the average volume of the chromosomes at interphase, using logarithmic scales (Fig. 3). A similar relationship applies in the old field in that species with larger interphase chromosome volume (4–7 μ^3) occurred only at the lower exposure rates (< 1000 R/day). While these correlations are conspicuous and emphasize the importance of the chromosomes as the site of damage, the variation in the relationship, the shifts from year-to-year in relative sensitivities, the anomalous radiation-linked mortalities as in scarlet oak, the variation introduced by annual as opposed to perennial growth, and other factors, all emphasize that cellular characteristics alone cannot be expected to explain all aspects of radiosensitivity or to provide a sufficient basis for predicting ecological effects. It is, nevertheless, striking that nuclear characteristics do fix the general range of sensitivity and that partial correlations relate plant size and community stature, sensitivity to irradiation and to other stresses, and chromosome volume to one another.

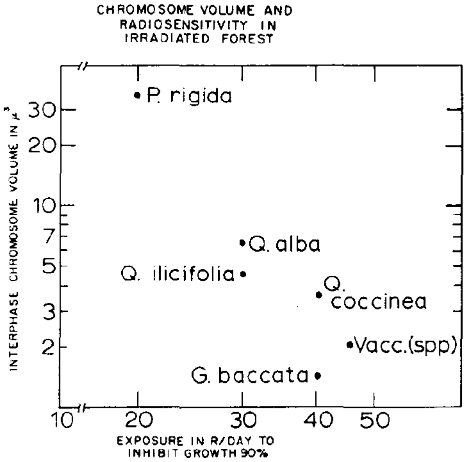

FIG. 3. CORRELATION BETWEEN AVERAGE VOLUME OF THE CHROMOSOMES AND DAMAGE FROM IRRADIATION IN THE IRRADIATED FOREST, BROOKHAVEN NATIONAL LABORATORY

(From Woodwell, 1967)

DISCUSSION

Some broader features of radiation sensitivity of communities converge with those of radiation sensitivity of organisms:

1) In both cases sensitivity has a complex meaning in relation to varied organic processes, parts of the system, and time in life cycles. For the organism, LD_{50} is not a measurement based on a unitary process comparable to radioactive half-life, but an index of gross response based on integration of effects on different parts and processes of the organism for a particular kind, rate, and life-cycle-timing of dose. For the community, CC_{50} is an index of gross response, integrating effects on different processes and populations and probably also influenced by seasonal timing, exposure rate, and other factors.

2) Radiation effects have biological meaning and relevance beyond simple destruction of cells, tissues or organisms. Radiation effects on individual organisms have meaning in relation to such general phenomena as mutation rate, evolutionary level, and the aging process (Woodwell and Rebuck, 1967; Sparrow, Underbrink, and Sparrow, 1967; Johnson, 1963; Curtis, 1966). Radiation effects on communities involve not simply destruction, but effects on balances between respiration and photosynthesis, balances of production by different community strata and components, and balances between populations.

3) At both organismic and community levels a wide range in relative sensitivity to radiation exists. Sensitivity of individual organisms, from bacteria to man, ranges over several orders of magnitude. Sensitivity of communities ranges through at least two orders of magnitude, as represented in the lichens and forest vascular plants of this study.

As a basis for the correlation of radiation sensitivity with evolutionary level, it is tempting to assume that the more complex the organism, the greater the variety, interdependence, and probable range of sensitivities of its essential functions and the more sensitive it may be to irradiation. Thus, lichens, mosses, and certain algae appear relatively resistant; higher plants appear to be sensitive; and mammals appear to be still more sensitive. Additional support for this seems to come from recognition that in mammals several different radiation-damage syndromes are dependent on dose-rate and total exposure (Bond, Fliedner, and Archambeau, 1965) and are traceable to the sensitivity of various tissues or tissue systems. No parallels are known among higher plants, although they may exist (Woodwell and Rebuck, 1967). In analogy at the community level the forest has greater complexity (diversity of species, growth-forms, and functional relations) than the lichen and old-field communities and is more sensitive to irradiation. The forest has also greater stability; it shows evidence of community-level homeostasis in the relative constancy of its populations and maintenance of an internal soil and microclimatic environment favorable for the persistence of those populations; this is lacking in the old field. As on the level of the organism, there is a paradoxically greater vulnerability to one kind of environmental variation (irradiation) resulting from the higher organization which confers stability in the face of other environmental variations (in relation to which species' adaptations have evolved).

The basis for the forest's sensitivity to irradiation appears to lie, however, not simply in complexity of the forest but in the greater sensitivity of woody plants (Sparrow and Sparrow, 1965). Dominance by sensitive woody species implies: (1) destruction of the dominant species themselves by lower radiation exposure than is the case in the old field, (2) more profound change in environmental factors affecting other species, resulting from changed soil and microclimatic conditions following death of the dominants, (3) more evident loss of the characteristics of the mature community than in the old field, in which other herb species replace the sensitive dominants without marked loss of community production or structure, and (4) more lasting, less easily reversible effects on the forest community, with destruction of its long-lived dominant plants.

In general, through the course of succession in terrestrial communities, there is progressive increase in community complexity and diversity, stature or massiveness, and in productivity, maturity of soil, and relative stability of populations (Whittaker, 1953). Most of these trends in succession are subject to reversals in some circumstances, especially from the later successional stages to climax. It appears, however, that succession progresses toward communities of greater sensitivity to radiation and that relatively high sensitivity should be expected of many climax communities, especially those dominated by woody plants. It is furthermore evident that the kinds of changes in communities that occur with increased exposure to ionizing radiation — reduction of complexity, diversity, productivity, stature and massiveness, and stability — are similar in character to the retrogressive succession that may be produced by other chronic disturbances such as overgrazing. Radiation effects are thus consistent with most general observations on the behavior of communities in relation to other environmental factors — processes of succession and retrogression, responses of community production and structure to environmental severity, and relations of species populations and community composition to natural environmental gradients.

The general lack of success in discovering simple, consistently unifying correlations between gross aspects of nuclear or chromosome morphology and ecological or evolutionary patterns in the major plant and animal groups (Stebbins, 1966), emphasizes the hazards of assaying ecological patterns from cytological data alone. The relationships observed between radiation sensitivity, kinds of plants, and nuclear characteristics thus become part of a whole complex of correlations, some simple and some complex, some strong and some weak, some probably causal and others coincidental, among chromosome volume, evolutionary level, plant stature, length of life cycle, radiation sensitivity on a genetic basis in the laboratory, radiation sensitivity of populations in the field, vulnerability as affected by ratio of photosynthetic to nonphotosynthetic tissue, and ecological relations of plant populations in relation to succession and environmental severity. It would be gratifying if an effective sorting and evaluation of these relationships as they bear on community sensitivity could be stated. It may be more appropriate to say that, apart from the relation of sensitivity to chromosomal volume, they have not received the study they deserve in view of the broad interest of the evolutionary and ecological problems involved.

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RECOVERY OF THE LAND PLANTS AT ENIWETOK ATOLL FOLLOWING A NUCLEAR DETONATION*

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Abstract—A long-term investigation was conducted at Eniwetok Atoll during 1954–57 to determine the rate of recovery of land plants damaged by the radiation, shock and heat blast of the Nectar detonation in 1954. At Belle Island seven plant species were tagged, measured and photographed before the detonation. At approximately monthly intervals after the detonation for a period of ten months, and again after an interval of six months, the plants were observed and photographed. The first indication of recovery was observed on the eighth day, at which time buds were noticeable on stems of *Scaevola* and *Messerschmidia* plants. In a month's time, most of the plants had formed new leaves and some had produced flowers and fruits. In six months, the general condition of the vegetation was similar to that which existed before the detonation. Two plants, *Guettarda* and *Portulaca*, which were unhealthy at ten months, had improved by the sixteenth month. Photographs of the recovery of some of the plants are included in this report, as well as a discussion of agents other than radiation which have been reported to cause similar damage to plants of the coral atolls of the Pacific Ocean.

Résumé—Une investigation à long terme a été effectuée à l'atoll d'Eniwetok pendant les années 1954–1957 afin de déterminer la vitesse de restauration de plantes de pleine terre endommagées par les radiations, le shock et le souffle thermique de l'explosion Nectar en 1954. A Belle Island, sept espèces de plantes ont été étiquetées, mesurées et photographiées avant l'explosion. Les plantes ont été observées et photographiées à des intervalles d'environ un mois pendant une période de dix mois après l'explosion et ensuite, après un délai de six mois. Le premier indice de restauration a été observé le huitième jour, moment auquel des bourgeons ont été relevés sur es tiges de *Scaevola* et *Messerschmidia.* Endéans une période d'un mois, la plupart des plantes avaient formé de nouvelles feuilles et certaines avaient produit des fleurs et des fruits. En six mois, les conditions générales de végétation étaient redevenues semblables à celles qui existaient avant l'explosion. Deux plantes, *Guettarda* et *Portulaca*, qui étaient maladives à dix mois, se sont améliorées au seizième mois. Des photographies de la restauration de plusieurs de ces plantes sont inclues dans ce rapport ainsi qu'une discussion des agents autres que les radiations connus comme étant cause de semblables dégats aux plantes des attols de l'Océan Pacifique.

Zusammenfassung—Eine langfristige Untersuchung am Eniwetok Atoll wurde während der Jahre 1954–57 durchgeführt um die Geschwindigkeit der Erholung der durch Bestrahlung, Schock und Hitzestoss der Nectar Detonation in 1954 beschädigten Landpflanzen festzustellen. Auf der Belle Insel wurden sieben Arten vor der Detonation markiert, gemessen und photographiert. In ungefähr monatlichen Abständen, während der ersten 10 Monate nach der Detonation und danach nach 6 Monaten wurden die Pflanzen wieder beobachtet und photographiert. Das erste Anzeichen der Erholung wurde am achten Tag gefunden, indem Knospen an den Stämmen von *Scaevola* und *Messerschmidia pflanzen* sichtbar wurden. Nach einem Monat hatten die meisten Pflanzen neue Blätter gebildet und einige hatten Blüten und Früchte. Nach 6 Monaten war der generelle Zustand der Vegetation ähnlich dem der vor der Detona-

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tion existierte. Zwei Pflanzen, *Guettarda* und *Portulaca*, die nach 10 Monaten noch ungesund waren, hatten sich nach 16 Monaten gebessert. Photographien einiger der erholten Pflanzen sind diesem Bericht beigefügt, sowie eine Besprechung der Mittel, ausser den Strahlungen, von denen ähnlicher Schaden wir der an den Pflanzen der Korallenattolle des Pazifik berichtet worden ist.

INTRODUCTION

SINCE the summer of 1946, the Laboratory of Radiation Biology of the University of Washington has conducted studies at the Eniwetok Proving Ground to evaluate the distribution of radioactivity in aquatic and terrestrial organisms of the atolls of the western Pacific and adjacent areas. These studies were made either shortly after a nuclear device had been detonated or after intervening periods varying from several to many months. The results of the investigations conducted in 1946,(7) 1947,(1) 1948,(2) 1949,(3) and 1952(5) indicated the need for a study of the reinvasion or regrowth of organisms in an area contaminated by radiation.

A study of this nature was undertaken following the detonation of an atomic device (Nectar) at Eniwetok Atoll in the spring of 1954. Facilities were made available at the Eniwetok Marine Biological Laboratory on Elmer (Parry)

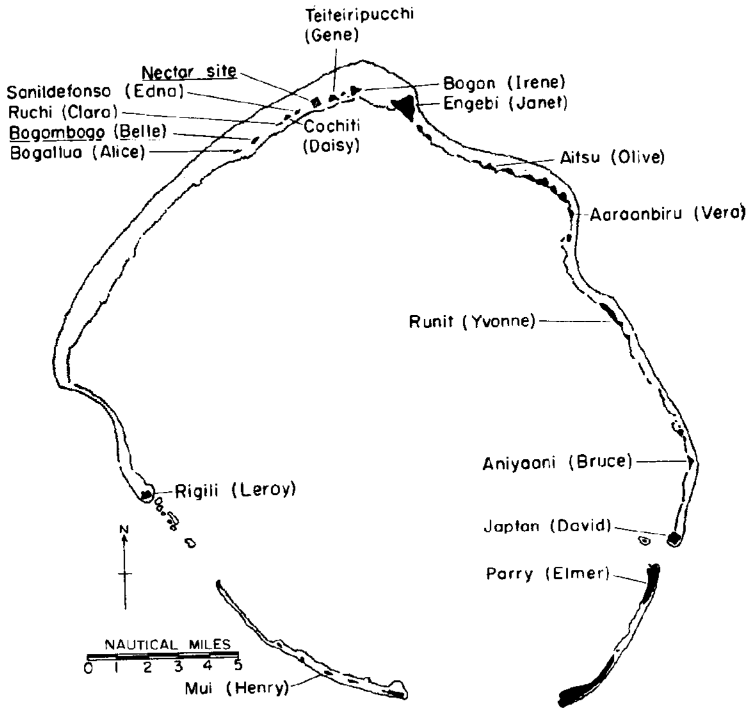

FIG. 1. Eniwetok Atoll.

Island by the Division of Biology and Medicine of the United States Atomic Energy Commission, and logistic support to carry out the sampling programme was furnished by Joint Task Force Seven of Operation Castle.

The study of the land plants was a part of the over-all programme of the Laboratory of Radiation Biology. In this report only the results of this portion of the programme are presented. The results of the investigations on the following organisms already have been reported: reef fish,(23) land crabs,(15) invertebrates(8), and algae.(19)

The objective of the land plant programme was to determine the length of time required for a plant damaged by a nuclear detonation to resume its normal functions of growth and reproduction while being subjected to chronic radiation.

The main site of study was Belle Island (Bogombogo), 2·7 miles W-SW of the detonation (Fig. 1). This area was estimated to be far enough removed from ground zero that the plants would not be uprooted by physical forces yet would be in an area of sufficient radioactivity for the proposed study.

METHODS

Representative plants of the eight most common species growing in the area were studied in detail; however, numerous other plants also were observed. Before the Nectar detonation the plants were staked, labelled, measured and photographed. After the detonation, and at approximately monthly intervals thereafter, observations and measurements were made of the plants and photographs were taken. *Scaevola sericea* Vahl, a woody shrub, was chosen as the principal plant for study because of its widespread occurrence on the islands of the Central Pacific Ocean. The other plants studied in detail were: *Messerschmidia argentea*, *Guettarda speciosa* and *Cocos nucifera*, trees; *Lepturus repens*, a grass; *Boerhaavia tetrandra* and *Triumfetta procumbens*, prostrate vines; and *Portulaca oleracea*, a fleshy herb. The locations of these plants on the island are shown in Fig. 2.

Gamma survey-meter readings also were taken to determine the gamma dose to which the plants were subjected.

RESULTS

The gamma survey-meter readings taken at Belle Island during the period of investigation are given in Fig. 3, which includes the theoretical gamma dose rate according to MILLER and LOEB.(16) The accumulated total dose from one minute after the detonation to the end of 200 days was calculated to be approximately 400 r.

Before the Nectar detonation, the plants on Belle Island were generally green and healthy-

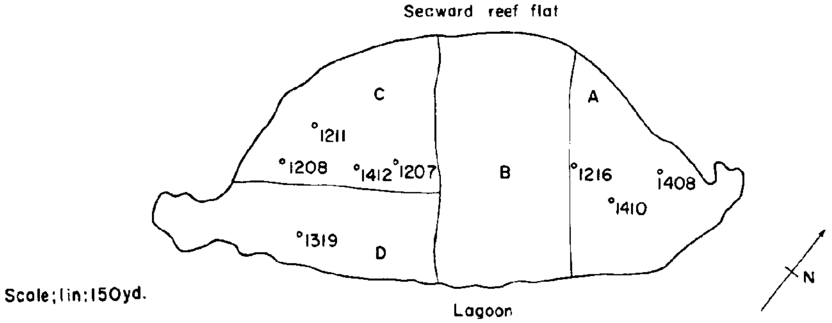

FIG. 2. Diagram of Belle Island, Eniwetok Atoll, showing the location of the land plant stations and the collecting areas.

Area A	Area C	Area D
1216 *Guettarda speciosa*	1207 *Boerhaavia tetrandra*	1319 *Scaevola* sp.
1408 *Messerschmidia argentea*	1208 *Triumfetta procumbens*	
1410 *Lepturus repens*	1211 *Portulaca oleracea*	
	1412 *Cocos nucifera*	

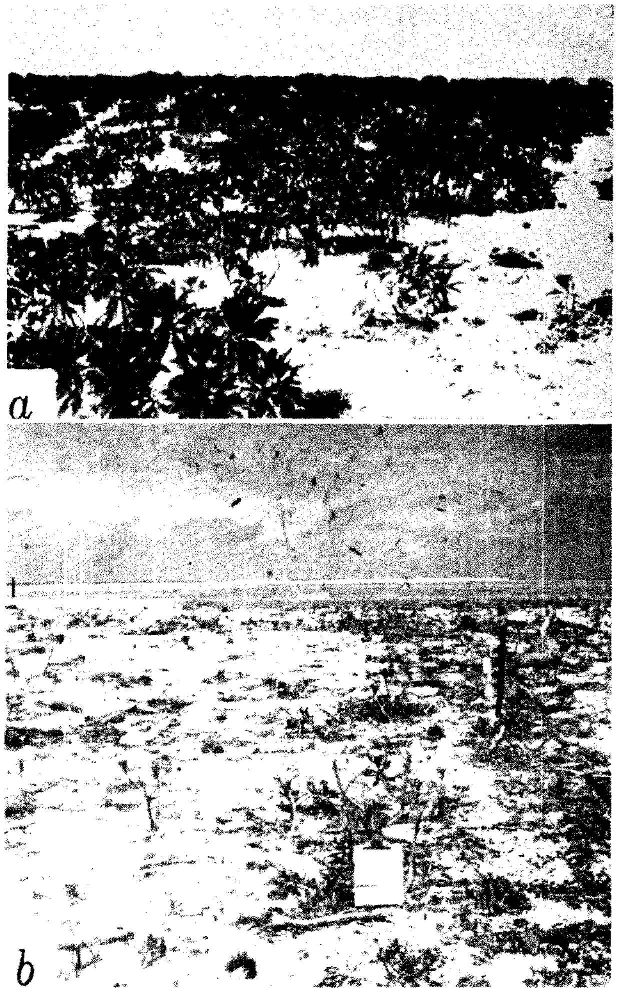

FIG. 4. General view of land plants at Belle Island, Eniwetok Atoll. (a) On April 15, 1954, before the Nectar detonation. (b) On May 22, 1954, eight days following Nectar, showing a *Scaevola* plant (No. 1319) in the foreground.

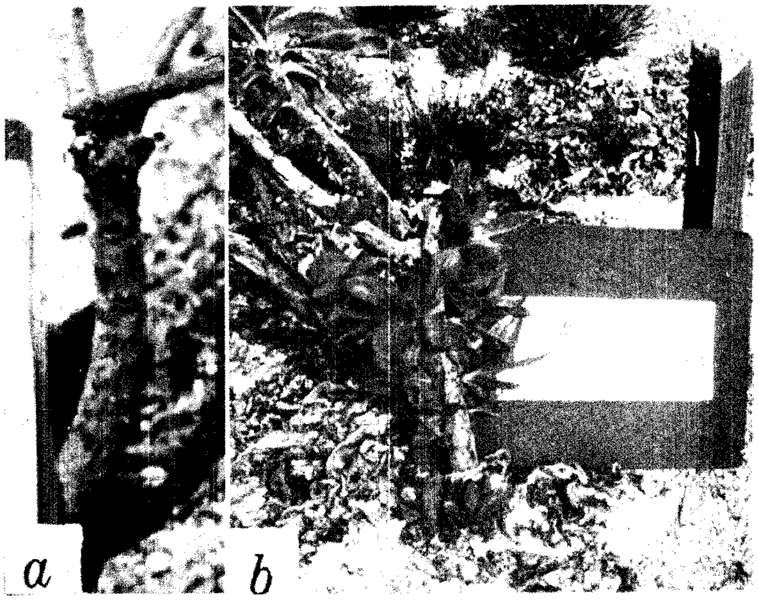

FIG. 5. *Messerschmidia* plant at Belle Island, Eniwetok Atoll. (a) Plant No. 1248 showing adventitious buds on May 22, 1954. (b) Close-up of the same plant on June 18, 1954.

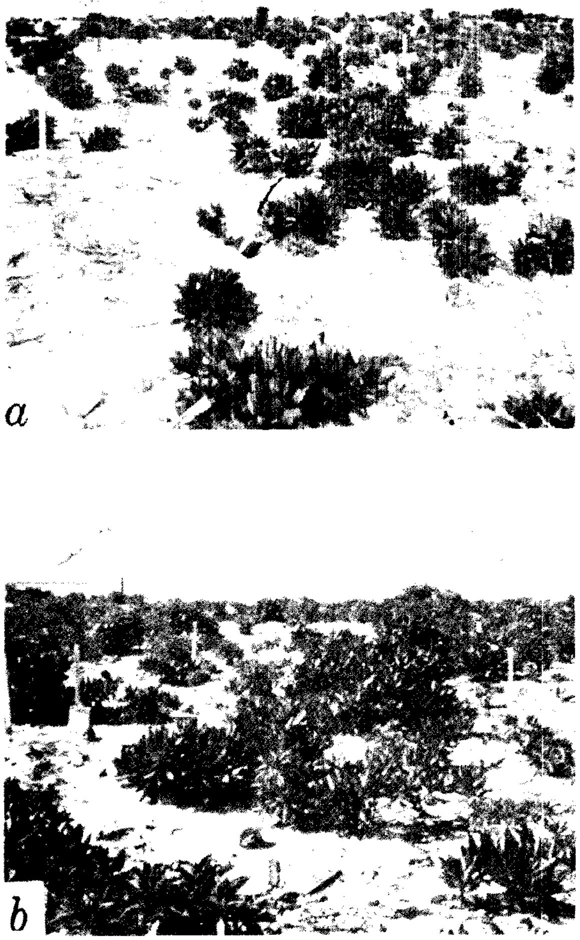

FIG. 6. Land plants at Belle Island, Eniwetok Atoll, Area D. (a) Three months after the Nectar detonation. (b) Six months after detonation.

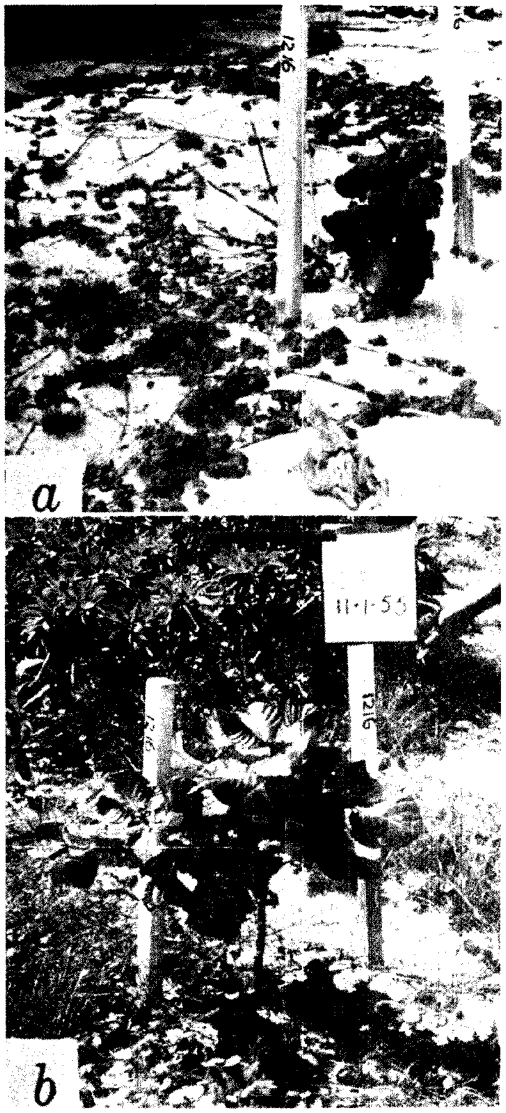

Fig. 7. *Guettarda* plant at Belle Island, Eniwetok Atoll. (a) Close-up of unhealthy plant (No. 1216) on March 15, 1955. (b) Close-up of the same plant on November 1, 1955.

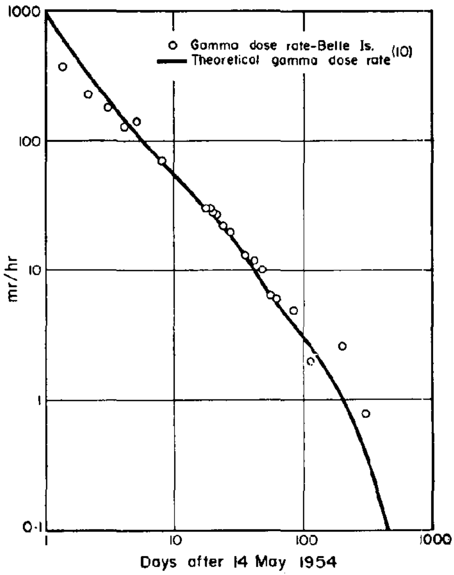

FIG. 3. Gamma dose rates at three feet at Belle Island, Eniwetok Atoll, May 15, 1954 to March 21, 1955, compared with the decay of fission products from the slow neutron fission of U^{235}(10).

looking. A photograph of the general area taken at this time (Fig. 4a) shows the healthy appearance of the vegetation. In some plants there was yellowing of the leaves and necrosis, especially in *Scaevola* and *Guettarda*, and some reddening of the tops of the grass, *Lepturus repens*. The latter symptom is typical of some species of plants growing in phosphorus-deficient soil, a condition often found on coral atolls and in areas where the top soil has been disturbed or blown away. The Mike detonation of 1952 had removed most of the plants and top soil from Belle Island, resulting in the depletion of some of the elements essential for plant growth. In spite of these deficiencies regrowth of the plants at Belle Island was rapid. In April 1954 some of the *Scaevola* and *Messerschmidia* "trees" were up to five feet in height, with a spread of ten feet, and bore many flowers and fruits. Plants of the other species also were well established.

A photograph of Belle Island taken eight days following the Nectar detonation (Fig. 4b) shows the extent of the damage sustained by the plants. From the air the island looked brown and desolate. On closer inspection it was found that most of the plants had been scorched by the heat wave and many of them had been blown over or broken by the shock blast. Two of the previously tagged plants (*Cocos* and *Portulaca*) had disappeared or had been dislodged from their original positions; other plants of these species were staked and labelled for study. On the tall shrubs, such as *Scaevola*, *Messerschmidia* and *Guettarda*, the leaves were usually gone or scorched, and the scorched branches and a few persistent leaves were all that remained of the plants. Flowers and fruits were found on some plants, especially in the prostrate plants such as *Portulaca*, which was located behind a large fallen coconut trunk. Close-ups of examples of damaged plants eight days post Nectar are shown in the foreground of Figures 4b and 5a.

Recovery of the plants was rapid. Heavy rains occurred on the third day. On the eighth day green buds, 1–3 mm in length, were observed on the stems of *Scaevola* and *Messer-*

schmidia (Fig. 5a) plants. On the thirty-fifth day the shoot leaves were 7–15 cm long, covering much of the old stems (Fig. 5b) and giving the plants a green and healthy appearance. By this time many of the other plants had formed new leaves and three species (*Portulaca*, *Triumfetta*, and *Messerschmidia*) had produced new flowers and fruits. The island now had lost its scorched appearance; from the air it looked green rather than brown as it had one month earlier.

In August, three months after the detonation, the plants were growing well (Fig. 6a) and some species, such as *Boerhaavia*, had produced new flowers. The leaves of most of the species had grown to maximum size, and the branches had grown almost to the pre-Nectar dimensions. This was not the case with the *Guettarda* and *Lepturus* plants, which recovered more slowly than the other species. The new growth on the *Guettarda* plant consisted of ten small leaves which originated from a new shoot 18 cm tall at the base of the old plant; the *Lepturus* plant was a mat of dead tops with some new growth forming at the periphery.

In six months the general condition of the vegetation (Fig. 6b) was similar to that which existed before the Nectar detonation. In March 1955, approximately ten months post Nectar, the plants appeared to be normal, most of them bearing abundant flowers and fruits, healthy, green leaves, and the usual amount of yellow, older leaves. The *Guettarda* plant, however, bore curled, distorted, and unhealthy-looking leaves (Fig. 7a). When observed again in November 1955, it bore about thirty healthy, green leaves, had increased in height and apparently was completely recovered (Fig. 7b). The *Portulaca* plant bore only a few leaves in March 1955, but when observed in November 1955, it had recovered somewhat, bearing abundant flowers and some green leaves.

No other aberrant growth forms were seen in the field observations at Belle Island. At Janet Island, the fasciated stems and the tumorous growths on plants of *Ipomoea tuba* observed in 1949 by BIDDULPH[6] were still present in 1957.

The measurements and observations made on one of the plants, *Scaevola* (No. 1319), during the course of the study are presented in Table 1.

DISCUSSION

Previous studies to evaluate the recovery and reinvasion of the flora at the Eniwetok Proving Ground, approximately fifteen months after Operation Sandstone, were made in 1949 by ST. JOHN[21] and BIDDULPH.[6] They reported morphological abnormalities in ten species of plants growing on islands where atomic detonations had taken place, and where radiation levels were undoubtedly higher than those on Belle Island during the Nectar survey. These abnormalities included flattening, shortening, thickening and spiral torsion of stems, severe "die-back" of leaves and stems, chlorosis, asymmetry, shrivelling, crumpling and twisting of leaves, chromatism of stems, proliferation and enlargement of inflorescences, abnormal proliferation of stems, and sterility of plants. St. John reported finding a mutant of *Guettarda speciosa* on Runit Island but did not describe it. Biddulph reported spiralling and splitting of fronds on several coconut palms on Aitsu (Olive) Island, which is located between two of the "shot" islands.

On the "shot" islands, the plants closest to the bomb crater centres (where radiation levels were highest) were most severely affected. In areas where radiation levels were lower, the "disturbance of ecological habitats" was reported to be more important in excluding plants from these areas than the radiation effects from the bombs.[6] Undoubtedly many of the abnormal plants started their growth after the nuclear detonations had occurred in impoverished soil lacking inorganic nutrients and organic matter. These conditions are known to cause nutrient deficiencies which can sometimes be identified by the appearance of the plant. In coral atolls where the top soil has been removed the retention of rain water in the surface layer of soil would be slight, resulting in the curling, drying, and ultimate death of the shallow-rooted plants. On the basis of these observations it may be concluded that some of the abnormalities observed could have been caused by factors other than radiation. Therefore, it would be impossible to ascertain all of the causes of damage to plants in an area where radiation and nutrient deficiencies both exist. In areas of high radiation levels, much of this damage

Table 1. *The regrowth of* Scaevola *sp.* (*Plant No.* 1319) *at Belle Island, Eniwetok Atoll, from May* 22, 1954 *to March* 15, 1955 *following the detonation of May* 14, 1954 *at a site two and one-half miles away*

Date	Appearance	Height (cm)	Over-all diameter (cm)	Length of larger leaves (cm)	Remarks
4/15/54	Healthy; green flowers and fruits present	75	90	16	
5/22	Plant badly damaged, stems naked and broken; some burned and green leaves persist at terminals	45	40	7·5	A few plants observed with persistent floral parts
6/19	New leaves on stems; branches still scrawny-looking	65	75	15	No flowers observed on on this plant
8/12	Most leaves green and healthy; plant not as bushy as in April	75	75	16	Flowers present on *Scaevola* Plant No. 1209, Area C
9/14	Plant as healthy and bushy as in April	75	90	20	Flowers present on *Scaevola* Plants No. 1209 and No. 1213, Area A, and others
11/2	Growth normal in every respect; small flowers present	75	90	20	
11/30	Plants healthy, larger than in April, many flowers	78	95	20	
3/15/55	Yellowing of oldest leaves only; plant healthy, no flowers or fruits	100	125	20	Some *Scaevola* plants 2 metres in height

could be attributed to the radiation, because it has been shown in controlled field experiments, with several plants, that chronic doses of gamma radiation of 13–37 r/day for two to five months can cause plant abnormalities of various kinds,(13) similar to those found at the Eniwetok Proving Ground. The total gamma dose delivered in these experiments ranged from 780 r to 5,550 r. In more recent studies with conifers Sparrow(20) observed that doses as low as 3 r and 4 r/day caused death of *Pinus rigida* after six years of exposure (total cumulative dose, about 8,000r). Many plants, however, were dead or dying at doses much below this cumulated dose, and some visible damage was observed at doses below 3 r/day.

Observations made in February 1956 in the Marshall Islands by Fosberg(9,10) also suggest possible radiation damage to plants twenty-three months after an incidence of high-level radioactive fallout. He found severe damage in the land plants (*Guettarda speciosa*, *Cocos nucifera*, *Suriana maritima* and others) at Gegen Island, Rongelap Atoll, where the "total radiation dose to infinity" was reported to be 3,360 r. Where the levels of radiation were 10–100 times lower, little or no damage was observed. However, some species (*Guettarda*, *Lepturus repens*, and *Fleurya ruderalis*) appeared to be normal at Kabelle Island where the radiation level was high (total dose 1,824 r). Other species (*Suriana*, *Cordia subcordata*, *Cocos nucifera* and *Pisonia* *grandis*) were abnormal in appearance at islands where the levels of radioactivity were lower. Fosberg suggested that some species of plants were more susceptible to radiation than others.

On the other hand many of the abnormalities reported by Fosberg, St. John and Biddulph have been reported from coral atolls where no radioactive fallout has occurred. For example, defoliation and death at the tips of branches of *Cordia*, *Pisonia* and *Tournefortia* (*Messerschmidia*) were reported on Wake Island in April 1952, after a period of drought, by FOSBERG.(11) TAYLOR(22) reported that the vegetation at Bikini Atoll in March and April 1946 (before Operation Crossroads) was unhealthy-looking and that *Pisonia* plants bore only scanty foliage, improving later in the year. Records of rainfall in the northern Marshall Islands show that the dry period prevails from December to April, the months of January and February getting the least rainfall.(4) As shown by the observations of Fosberg and Taylor, one would expect to find the plants at their worst during the dry period.

Some abnormalities found in the plants on coral atolls have been caused by insects. Taylor reported that the leaves of *Suriana* were clipped as if by insect attack, and Fosberg reported that *Bauhinia* was chlorotic and badly eaten by insects. NIERING(18) reported that on Kapingamarangi Atoll the leaves of *Scaevola* were attacked by a leaf miner and new shoots and buds of *Calophyllum* sp. and *Barringtonia asiatica* were "infested to the point of disrupting the normal growth pattern." On Onotoa Atoll, MOUL(17) observed that several insects were found on *Guettarda* plants. These included wasps, moths, stink bugs, and butterflies. Moul reported also that leaves of *Pisonia* trees were so badly damaged by leaf-cutting bees that he could not find a perfect specimen of foliage. At Rongelap Atoll members of this Laboratory noted infestations of a lepidopteran larva causing deformed leaves on *Guettarda* plants. They also reported that insects caused defoliation and bud damage in plants of *Terminalia* sp. and *Pisonia*.

The bird population also is a factor in the production of unhealthy plants. Niering reported that at Kapingamarangi Atoll the leaves of *Asplenium*, *Nephrolepis*, *Guettarda* and *Pisonia* were turning brown and dying because of the fecal droppings of the white-capped noddy tern (*Anous minutus marcusi*). He reported that the breadfruit tree also is damaged by these birds. On Canton Island the suggestion was made that the native birds were chiefly responsible for the dead or dying conditions of the forest and scrub vegetation.(14)

Other agencies also have been reported to cause chlorosis, die-back, slow growth, aberrant growth forms, and other kinds of plant abnormalities. Some causes not mentioned previously are salt spray, wind, storms, flying gravel, soil conditions and land crabs.

Measurements of the amount of thermal radiation and blast received by the plants at Belle Island during the Nectar detonation were not made, but approximations of these values can be made on the basis of the energies required to produce the observed damage. A thermal energy of 10–15 cal/cm^2 is required to char vegetation and a wind velocity equivalent to 130–140 miles/hour is required to produce blast damage(12) similar to that observed at Belle Island. Also, from calculations based on data obtained from other nuclear detonations,(12) the initial gamma dose delivered at Belle Island was approximately 30 r, which is much lower than the levels required to cause visible plant damage in laboratory-type experiments. Essentially all of the damage to the land plants, therefore, can be attributed to the heat and blast rather than to the initial nuclear radiation. The excellent recovery of all but three of the plants (*Guettarda*, *Lepturus*, and *Portulaca*) is noteworthy, especially since the plants were subjected continuously to external radiation as well as the internal radiation from absorbed radioisotopes. The abnormal appearance and slow recovery of these plants, among the many observed, would appear to be due to radiation; however, the author feels that the other factors, which were not measured adequately during this investigation, should be evaluated carefully before ascribing the damage to radiation.

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Survival of Rats at Eniwetok Atoll[1]

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THE STORY of rats at Eniwetok Atoll (Marshall Islands) and their apparently uncanny ability to survive atomic detonations and inhabit areas with high levels of radiation has been referred to in various documents (Berrill, 1966; Hines, 1962 and 1966; French, 1965; Woodbury, 1962); all are to some degree incomplete or in error. The purpose of this paper is to pull together the fragments of data that are available and, at this late date, attempt to piece together the story of the survival of rat populations at Eniwetok.

HISTORICAL BACKGROUND

Eniwetok and Bikini atolls in the northern Marshall Islands were involved in the United States nuclear testing program between 1946 and 1958. During this period six major operations were carried out at Eniwetok Atoll and involved some 40 detonations. Many devices were small and made little impact on the environment; others, through shock, heat, and radiation waves, destroyed biotic communities within several miles of the test sites. The "Mike" explosion, rated at 10.4 megatons and by far the largest shot undertaken at Eniwetok, obliterated two islets, carved a crater in the coral reef a mile in diameter, and left scorched and singed plants and animals 14 miles away.

As with many operations, code names were given to each series and shot. The initial test program at Eniwetok in 1948 was labeled Sandstone; the Greenhouse series followed in 1951. In 1952 the Mike shot, involving a thermonuclear device, was part of the Ivy series. In 1954 the Nectar shot was the principal detonation of the Castle series. The Redwing series in 1956 and the Hardtack series in 1958, both involving a number of small shots, were the last in the test program (Hines, 1962).

While proof is lacking, I believe that the only rodent at Eniwetok Atoll prior to the initiation of the AEC program in 1946 was the Polynesian rat (*Rattus exulans*). This is the common rat of the Pacific islands, having moved with the Micronesians from island to island. Probably only the larger islets of the atoll (those with coconut plantings) were infested.

Although the Germans, and later the Japanese, were active in the Marshall Islands in the first half of the twentieth century, no specific records of rodents for Eniwetok Atoll seem to exist. St. John (1960) indicated that no botanical accounts existed from German (or the earlier Spanish) explorations. While botanical collections were made by the Japanese, I can find no descriptions of rats, and no rodent specimens from Eniwetok Atoll were present when I examined the collection in the Japanese National Science Museum in Tokyo. No specimens or recorded observations of rats from Eniwetok Atoll are known to exist prior to 1945.

Prior to the first test, a biological survey was made, and J. P. E. Morrison (U. S. National Museum, personal communication) has indicated that, in 1946 when he visited Eniwetok, he saw only Polynesian rats—on one islet (Igurin) on which he camped overnight. His observations at Bikini Atoll the same year were much more extensive. Though he observed rats on a number of islets there, he indicated that all were Polynesian rats. I have examined five specimens in the National Museum, each collected on a different islet, and I concur in the identification.

A similar, mono-specific rodent infestation can be cited for other relatively isolated areas in Micronesia prior to World War II or the postwar period. Thus it seems reasonable to conclude that only Polynesian rats were present at Eniwetok prior to 1946.

That an alternative hypothesis can be developed must be admitted. The Japanese had extensive fortifications at Eniwetok Atoll, largely on Engebi, Eniwetok, and Parry islets (Fig. 1). In

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[1] Adapted from presentation at Second National Symposium on Radioecology, Ann Arbor, 1967.

[2] Department of Biology, Bowling Green State University, Bowling Green, Ohio 43402. Manuscript received September 17, 1968.

Jackson, W. B. 1969. Survival of rats at Eniwetok Atoll. Pacific Science 23(3):265-275.

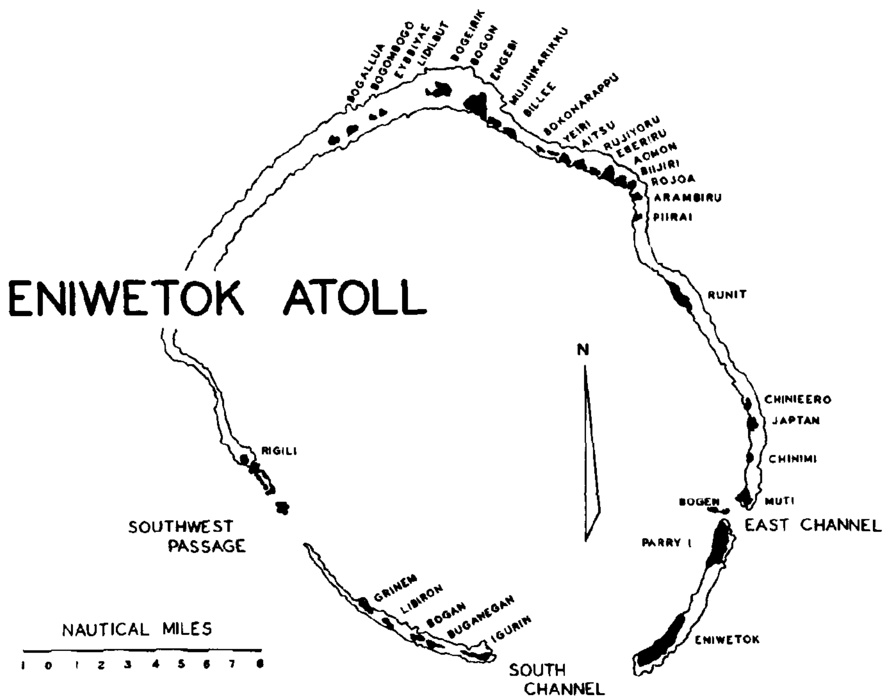

FIG. 1. Map of Eniwetok Atoll. Island names are taken from U. S. Naval Oceanographic Chart 6033 (revised January 1966).

1944 more than 3,500 troops and laborers were present on Engebi because of its air strip; Micronesians were restricted to the Biijiri, Aomen, Rojoa complex (Hines, 1962:84). Elsewhere in the Pacific, Japanese occupation on occasion brought with it the roof rat (*Rattus rattus*) (Johnson, 1962); this possibility cannot be excluded here. However, the roof rat populations now present at Eniwetok Atoll, and the Marshalls as a unit, are morphologically similar to the roof rat of the western world (*Rattus rattus rattus*) rather than to subspecies of the Asian mainland or western Pacific (*Rattus rattus mansorius* and other subspecies) (Johnson, 1962 and personal communication). While post-war invasions of western roof rats could have swamped and replaced earlier introductions, this seems unlikely, considering known interactions between the two subspecific groups in the Carolines (Johnson, 1962).

During the Japanese occupation, a major air field installation was constructed on Engebi. As a result, the islet was largely denuded, though a palm grove covering nearly one-sixth of the islet remained near its center, and some palms and/or second growth vegetation along the lagoon shore and the northwest tip of the islet appear in war-period photographs. Although some palms remained standing after the invasion, much of the vegetation was badly shattered (Bryan, 1944). Aerial photographs taken two months after the invasion show no trees and only isolated patches of ground cover. Thus rat habitat was relatively limited.

In the early test years, no specific observations of Eniwetok rats can be found, though reference is made to a collection of rats on Engebi in 1948 and 1949 (Hines, 1962:106). During the Sandstone series in 1948, one low-yield device was exploded on Engebi on April 15 from a 200-foot tower. At H + 1 day the gamma radiation in the islet center was estimated roughly at 12 R/hr; the accumulated dose, at H + 1 yr, 132 R (Laboratory of Radiation Biology, University of

Washington). Following the test, no exposed vegetation remained standing. Of the 43 plant species recorded from Engebi prior to the test, only 20 were not exterminated by the blast (St. John, 1950).

The Greenhouse tests in 1951 on Engebi (two detonations) produced an initial gamma radiation of 6,400–10,000 R in the islet center (Hines, 1962:210). At H + 1 yr the accumulated dose was 44 R. But the Polynesian rats apparently continued to exist on Engebi, since the affected area was small and probably only those rats close to the detonation sites were killed.

Probably about this time, the roof rat (*R. rattus*) was introduced. It may have arrived a few years earlier at the main supply areas of the atoll on ships from the United States or from other areas of the Marshalls where it was abundant. But we have no records of observations, and so this statement is conjectural.

In 1952, in preparation for Mike shot (Ivy series), rats on Engebi were collected; no radioactivity in their bones was found (Hines, 1962: 151), though slight activity occurred in other tissues (UWFL-33, 1955). Rats were also collected on Biijiri and Rojoa. All individuals were referred to as Polynesian rats. However, the single Engebi rat for which size data were recorded (UWFL-33) was obviously *not* a Polynesian rat; its weight (175 grams) was too great. In all probability it was a roof rat. Rats from the other two islets were most likely Polynesian rats, as judged from their weights (82 grams or less).

A thermonuclear device exploded on November 1, 1952, formed Mike crater on the former site of Elugelab and Teiteiripucchi islets, 3 miles northeast from Engebi. On November 8, no living animals were seen on Engebi; rats, ill and lethargic, were found on Biijiri. On November 10, six rats were found in traps on Rojoa that had been set on November 7 and had been empty on November 8. These two islets are approximately 9 miles from Mike crater. (No size data appear to have been recorded for these specimens; the presumption is that they were all Polynesian rats.)

The gamma dose rate on Engebi at H + 1 day was 1,000 R/hr; the accumulated dose at H + 1 yr, 11,000 R. (At Biijiri the annual accumulated dose was 1,440 R.) The shot caused a tidal wave over Engebi, and only stumps of vegetation remained. Rigili islet, 14 miles from Mike crater, had plants and birds scorched by thermonuclear heat.

Many observers supposed that rats on Engebi had been wiped out by the combined effects of the 1952 test. But in 1954 rats were found on Engebi. This has led to prolonged speculation (Hines, 1962:207–210). That the Polynesian rat was indeed exterminated by the thermonuclear test is a possibility. Roof rats perhaps survived, and their numbers may have been supplemented later by individuals from the supply boats traveling to Engebi.

The Laboratory of Radiation Biology (LRB) records give weights for 75 rats (identified as Polynesian rats) collected on Engebi in 1954. Of these, 71 were surely roof rats, as the animals were far too big (heavy) to be Polynesian rats; four were small enough, but no data on sexual maturity were given, so that no certain designation is possible. A poorly preserved remnant of one of the larger rats has been examined, and it was a roof rat.

During the pre-Nectar period in 1954, there was considerable experimental transportation of rats (all termed Polynesian rats) from Engebi to adjoining islets. Some 53 rats were involved, and the investigator (Major C. Barnes, LRB) records in his field notes that some of the rats on Engebi were of a "new gray species." This could be taken to indicate that two rat species were present at this time. I prefer to discount this hypothesis, since the measurements as well as two photographs of rats (identified as Polynesian) show them quite clearly to be roof rats. No weights or other data from the "gray species" have been found. Irradiation-induced depigmentation (Upton et al., 1960) due to inactivation of the follicle pigment cells might explain the appearance of gray animals.

Following the Nectar detonation of Castle series on May 13 in Mike crater, five rats from Engebi (H + 3 days) and twelve from Arambiru (H + 4 days) were transported to Bogombogo. On H + 7 days eight rats were caught on Engebi and transported to Bogombogo. No further notes were made about their survival, and no rats have subsequently been trapped on this islet. On the same day (H + 7), five rats that had severe radiation burns were captured on Engebi and returned to the laboratory for processing (Barnes, LRB). No rat collections were made after H + 7 days until September and October 1954, when six specimens (all of roof rat weight) were logged. Gamma radiation on Engebi on H + 1 day was 10.7 R/hr; H + 1 yr, 118 R (accumulated).

In 1955, rats (termed Polynesian) were reported present on Engebi in tremendous numbers (Hines, 1962:210). Pictures taken in 1957 of eight rats show that all individuals were roof rats. The first complete specimens of Engebi rats that we have been able to find were five animals (originally identified as Polynesian) collected in 1959 by LRB personnel. These are now in our possession and are quite clearly roof rats. Our field studies on Engebi (1964–1968) have shown through extensive trapping on the islet that only the roof rat is now present on this islet.

ANALYSIS OF RAT SPECIES

For a non-mammalogist, the distinction between these two rat species is not easy. Some differences in size and body and tail proportions exist, but the pelages may look amazingly alike; behavioral aspects may also provide a clue. It would be very easy for an individual who was not looking for species differences to be unaware of the problem. No mammalogists were involved in any of the field surveys, and, judging from field notes, correspondence, and conversations, no one (with the exception of Morrison) was aware of the rodent species which might be encountered at Eniwetok. Quite clearly, all of the workers expected to find the Polynesian rat.

I propose that this misidentification has seriously clouded the picture. In the absence of adequate records and specimens, we can only guess about the history of rat populations on the atoll. In all probability, the Polynesian rat was exterminated by the Mike test in 1952. On the strength of a single record, we can hypothesize that the roof rat had been introduced to Engebi prior to the 1952 Mike test. Had it been exterminated, the only source of this species on the atoll would have been Eniwetok and Parry islets, and perhaps Biijiri and Runit islets; so natural invasion by swimming was not a possibility. Currents surrounding Engebi are such that rats could not have crossed from adjoining islets, even if these islets had had rats. Exposed reefs at low tide do not provide the necessary pathway between islets. Movement on storm driven flotsam is possible but not considered likely.

As a result of earlier construction activity and tests and finally the thermonuclear blast in 1952, Engebi was stripped of vegetation. The only remaining source of protection would have been various construction artifacts, test buildings, photographic and instrument bunkers, and cable tunnels. Many have assumed that rats which had burrowed under such structures would have been sufficiently shielded to permit survival.

The Polynesian rat is not a burrowing animal but makes a nest under surface vegetation or debris. The roof rat, while often nesting in much the same way, may burrow. Usually the tunnels we found were adjacent to a concrete wall or slab, or under or adjacent to a coral block or tree root. This kind of physical support may be necessary if the burrow walls are not to collapse in the friable coral sand. Thus, if any rats were to survive a nearby detonation, the roof rat was the likely species.

Rats are highly adaptable and successful animals. While they orient poorly when visual contact with land has been broken (while swimming in the lagoon, for example), they often do live in marsh areas and successfully survive seasonal flooding (Steiniger, 1949). Perhaps the ability of hibernating ground squirrels to survive early spring floods (Quanstrom, 1966) has some parallel in the possible tidal wave survival of rats on Engebi. Air trapped in burrows might have prevented complete flooding and provided the necessary oxygen supply.

How many could have lived to form the nucleus of a new population can only be surmised, though sufficient protection probably existed for some hundreds of rats. The major limiting factor, after the period of heavy radiation, would have been food. Although some resprouting of plants occurred within two weeks and regrowth had begun within two months (Frank G. Lowman, Puerto Rico Nuclear Center and LRB, personal communication), until sufficient vegetation reappeared, the rats would have had to exist on beach debris (of which there was probably a considerable amount) and beach invertebrates, and by cannibalism. Their omnivorous food habits make this a reasonable possibility.

Not until a year after the Mike test did intensive preparations start for the Castle series of tests, and no observations of flora and fauna on Engebi for the intervening period are available. Rats could have been transported to Enbegi in the movement of supplies in early 1954. Field notes of LRB personnel (especially Barnes) indicated that rats were relatively common immediately prior to the Nectar shot in 1954; by 1955 the population asymptote probably was being approached, for Lowman (LRB) recorded his "rat colony" observations during this period (Hines, 1962:206–213). Thereafter, the population probably declined to the present-day level.

Lowman's estimate of the Engebi rat population was meant only as an approximation. In an area 100 feet square, he saw up to 60 rats at once during the day. Extrapolating to the 15 acres of available grassland yielded an estimate of 1,000–4,000 rats (Hines, 1962:209). Since total land area on Engebi is 260 acres, and some scrub areas were present, further extrapolation to an island population of 10,000 animals was not difficult (French, 1965). A current estimate, based on trapping data, suggests that the population now does not exceed 4,500 rats.

Additional construction and vegetational succession may have caused a lowered carrying capacity. Lowman's old "rat colony" area is now overgrown with *Scaevola taccada* and *Tournefortia argentea* trees 15–20 feet in height (Figs. 2 and 3). While the airfield remains a grassland complex, the rest of the islet is covered to various degrees by second growth. That the sand burr (*Cenchrus echinatus*) might have been virtually exterminated by the rats is possible, since Lowman observed rats frequently feeding on the seeds. In 1964 none could be found (though in 1966 a few small patches were discovered). The loss of this single plant species by intensive feeding might of itself have reduced the islet's carrying capacity significantly. In any event, rats are no longer as abundant as

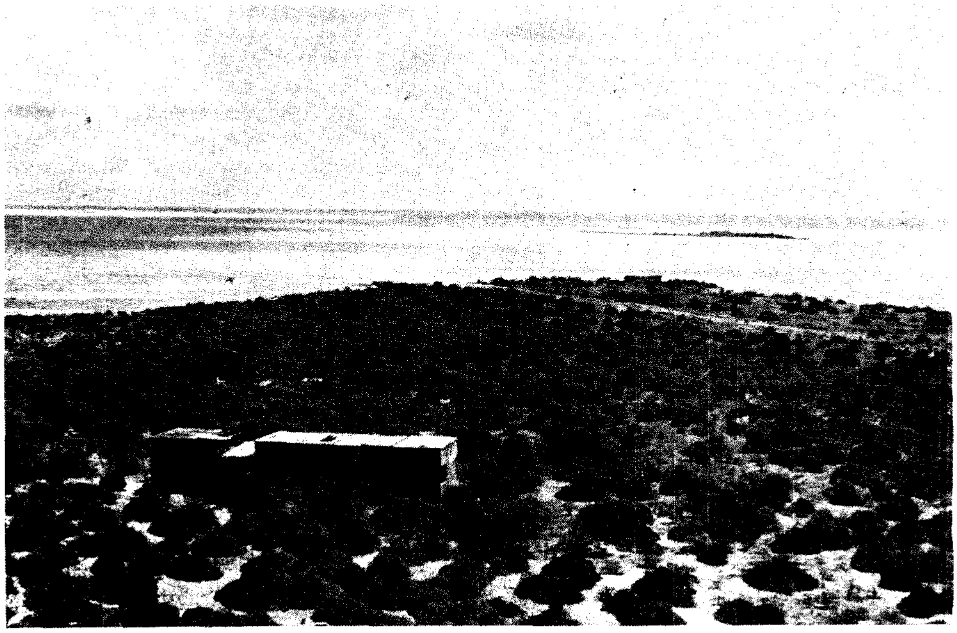

FIG. 2. Engebi islet viewed looking west toward "Mike" crater (1967). Lowman's rat colony area is just beyond and to the right of the large test building. Remnants of the air strip can be seen on far side of islet.

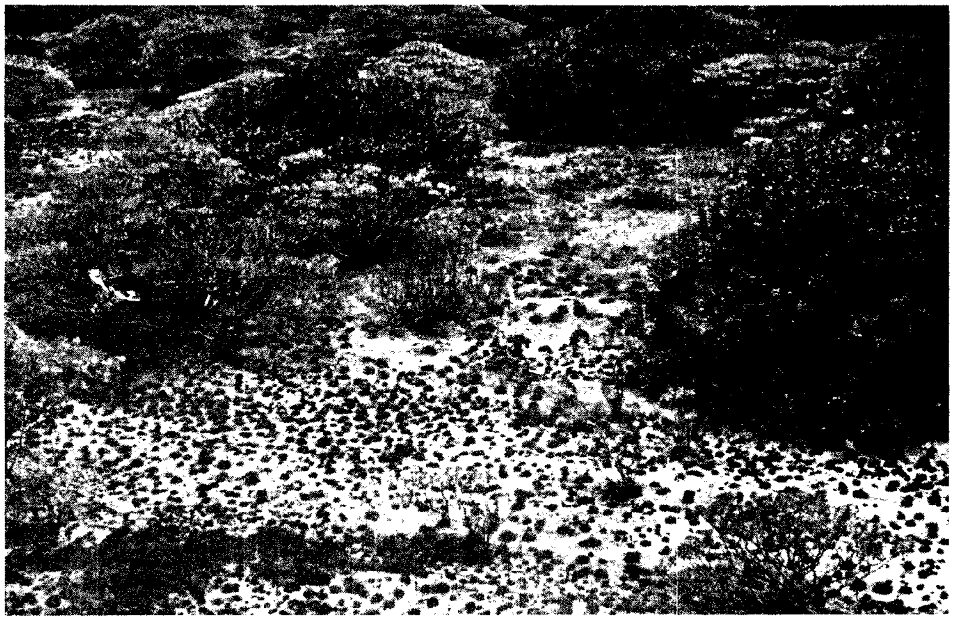

FIG. 3. Vegetation in rat colony area (1965). Shrubs are *Tournefortia argentea* and *Scaevola taccada* and are up to 15 feet in height.

they were in 1955; rodent activity during the day (prior to late afternoon) and large numbers of rat burrows are not now observed.

RADIATION EFFECTS

For very practical reasons few studies have been able to evaluate radiation-induced population changes of rodents under field conditions (Dunaway, 1965). Several studies (briefly reviewed by Provost et al., 1965) have subjected individuals to acute radiation and returned them to their natural environment. Doses below 500–750 R generally were ineffective in reducing reproductive rates or population size.

Only one field study under conditions of chronic low-level radiation has been reported in detail. Dunaway and Kaye (1964) evaluated a cotton rat population living in an area with a radiation level of 15 mR/hr; no unequivocal effect of radiation on body weight or breeding could be demonstrated. Analysis of roof rat data from H. T. Odum's El Verde study in Puerto Rico revealed no change that could be related to radiation exposure (Jackson, unpublished manuscript). Several recent reports are concerned with the assimilation of radioisotopes by small mammals at the Nevada Test Site (French et al., 1965; French, 1966; Turner et al., 1966). Because of low concentration levels, only temporary physiological changes were noted, though concentrations in specific tissues (e.g., I-131 in the thyroid) did occur.

Laboratory studies (cited by Dunaway and Kaye, 1964) of the impact of radiation on mammalian reproduction suggest that cumulative doses above 300 R result in sterility. Except for the Mike shot, estimated annual and accumulated gamma doses (exclusive of prompt radiation) for rats living on Engebi did not exceed 132 R (Sandstone). For Nectar the dose was 118 R. At daily doses of less than 1 R, some reproductive cycle disturbances do occur, and partial loss of fertility would by expected at sublethal levels (see Dunaway and Kaye, 1964).

Certainly any rat caught unprotected above ground by a detonation would have been killed immediately or in a short time by radiation effects. The gamma dose above ground during the first hour ranged from 6,400–10,000 R

(Greenhouse) to 2,800–6,700 R (Mike) to somewhat lower levels in subsequent tests. Animals protected in burrows were estimated to have received an integrated dose (beta and gamma) in the nine days following the Mike shot of 250–2,500 R; in the week following the Nectar shot, 55–80 R (Hines, 1962:210–211). Rats in deeper burrows would have had more protection, but those moving above ground to feed would have proportionately increased their load. Certainly, these estimates provide a basis for assuming survival of some individuals, for the $LD_{50\ (5\ days)}$ for laboratory rats is 800 R (Bond et al., 1965).

POPULATION DYNAMICS OF RATS

At the Hanford symposium, "Radiation and Terrestrial Ecosystems," French (1965) considered the growth potential and recovery of the Engebi rat population. Since he assumed the wrong species, based on published sources, his calculations of reproductive and survival rates were not strictly applicable. In the time period available, could the roof rat have populated Engebi to the density observed?

Let us assume maximal reproductive rates, even though the roof rat population on Engebi probably has now stabilized and shows a very low level of reproduction. Under conditions of habitat exploitation, high reproductive and low death rates would be expected (Davis, 1951).

Data on the reproduction of Pacific roof rats are inadequate. Average litter size, for example, varies considerably. For a different subspecies on Ponape, the value was 3.8; in Malaya, 5–6. For the same subspecies in temperate regions the litter size was 6–7; in the southern Marshalls (Majuro) in a limited sample, 5 (Jackson, 1962, 1965). In our current Eniwetok studies, litter size has averaged 4.8 (32 pregnancies). As an estimate for the increasing Engebi population, we used a litter size of six.

Mortality data are even more limited. Harrison (1956) cites some data for a similar species (*R. diardii*) in Malaya (Fig. 4), but this is a mainland population, and the mortality rates calculated probably are considerably higher than those experienced in an island situation.

Let us assume the same natural mortality estimate used by French (1965)—an annual probability of disappearance of 0.4. This figure was a composite of estimates for Polynesian rats on Ponape in the eastern Caroline Islands (Jackson and Barbehenn, 1962) and Harrison's (1956) estimates for the same species in Malaya. On this basis, using a litter size of six, the annual rate of population multiplication (R_a) is 7.5 (more than twice that calculated by French).

Following through with calculations and assumptions made by French, estimates of surviving populations necessary to produce the 1955 estimated population have been made (Fig. 5). The interval between shots was 18 months; between the 1954 shot and the 1955 obervation, 12 months. French had taken a three-year period; consequently his estimated initial populations were actually too small. For example, where $R_a = 4$, initial population would have had to be 300, not 150; where $R_a = 3$ (1 y post-Nectar), $R_a = 2.1$ (1.5 y post-Mike), or 1,050 rather than 700 rats. Assume also, as did French, a 50 percent reduced fertility (multiplication rate) following the Mike shot; following the Nectar shot, a 25 percent reduction.

With these restrictions and assuming that no mortality resulted from the Nectar shot, 250 survivors of the Mike thermonuclear shot could have produced a population of 10,000 rats in 1955. If no loss of fertility were assumed, only 63 surviving rats would have been necessary.

If a lesser initial population mortality rate were assumed (a straight line relationship with 40 percent of the initial cohort remaining after 12 months—Fig. 4), an annual multiplication rate (R_a) of 11.0 results, and an initial population of only 25 rats is required. With adjustments for reduced fertility—$R_a = 8.2$ (1 y), $R_a = 5.5$ (1.5 y)—an initial population of 961 animals is indicated (Fig. 5). This initial survival rate is only slightly higher than that found by P. Q. Tomich (unpublished manuscript) for roof rats in Hawaiian cane fields (mean survival: females 8.00 months; males, 6.63 months).

Rats certainly were killed by the Nectar shot (1954). Most of these estimates require between 1,000 and 2,000 survivors after this shot, a figure perhaps not too unreasonable, considering the cable tunnels, bunkers, and other protected sites available, the relatively low level of

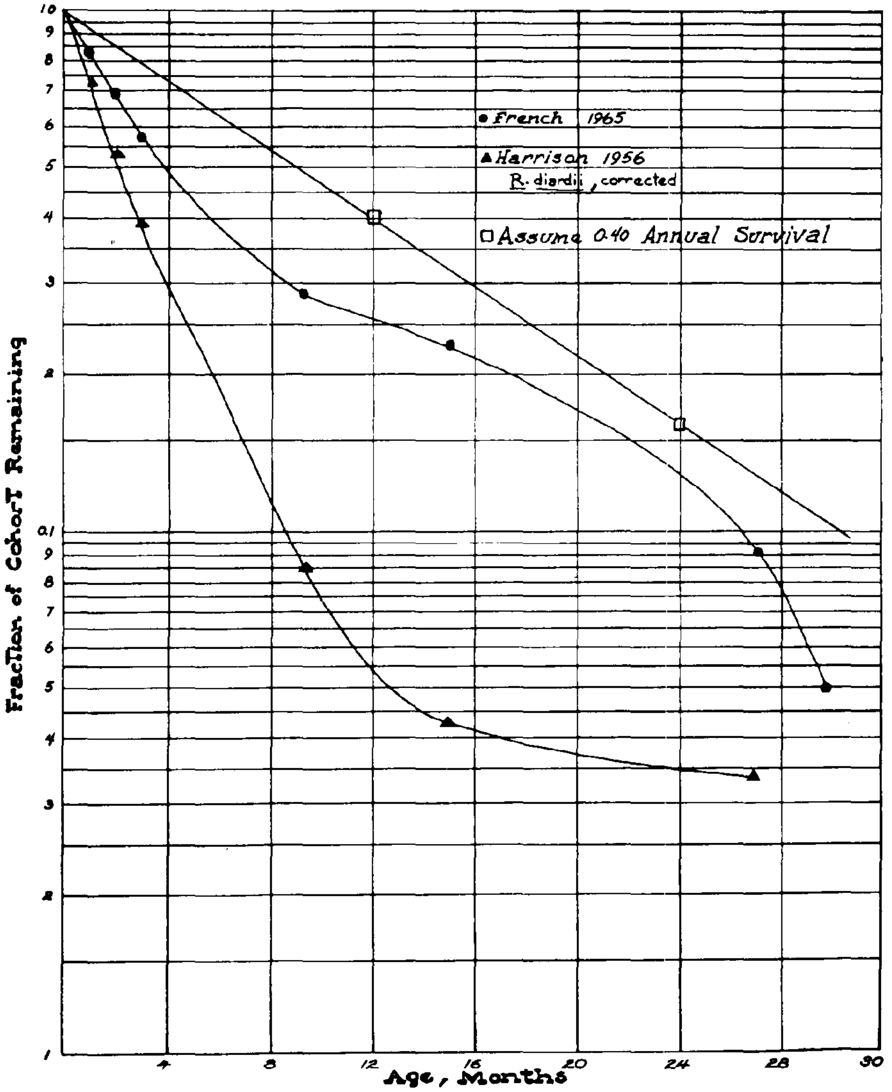

FIG. 4. Survival curves for roof rats (after French, 1965).

radiation, and the relatively limited physical damage to the islet—the central area was not covered by the tidal wave.

Regardless of the rat species designated, repopulation of Engebi by the survivors of the Mike test (1952) was theoretically possible. Indeed, by involving the roof rat with its larger litter size, even fewer survivors were needed. Though such survival cannot be actually documented, the circumstantial evidence strongly suggests that it did occur.

SUMMARY

The story of the survival of rats at Eniwetok during the nuclear testing program (1948–

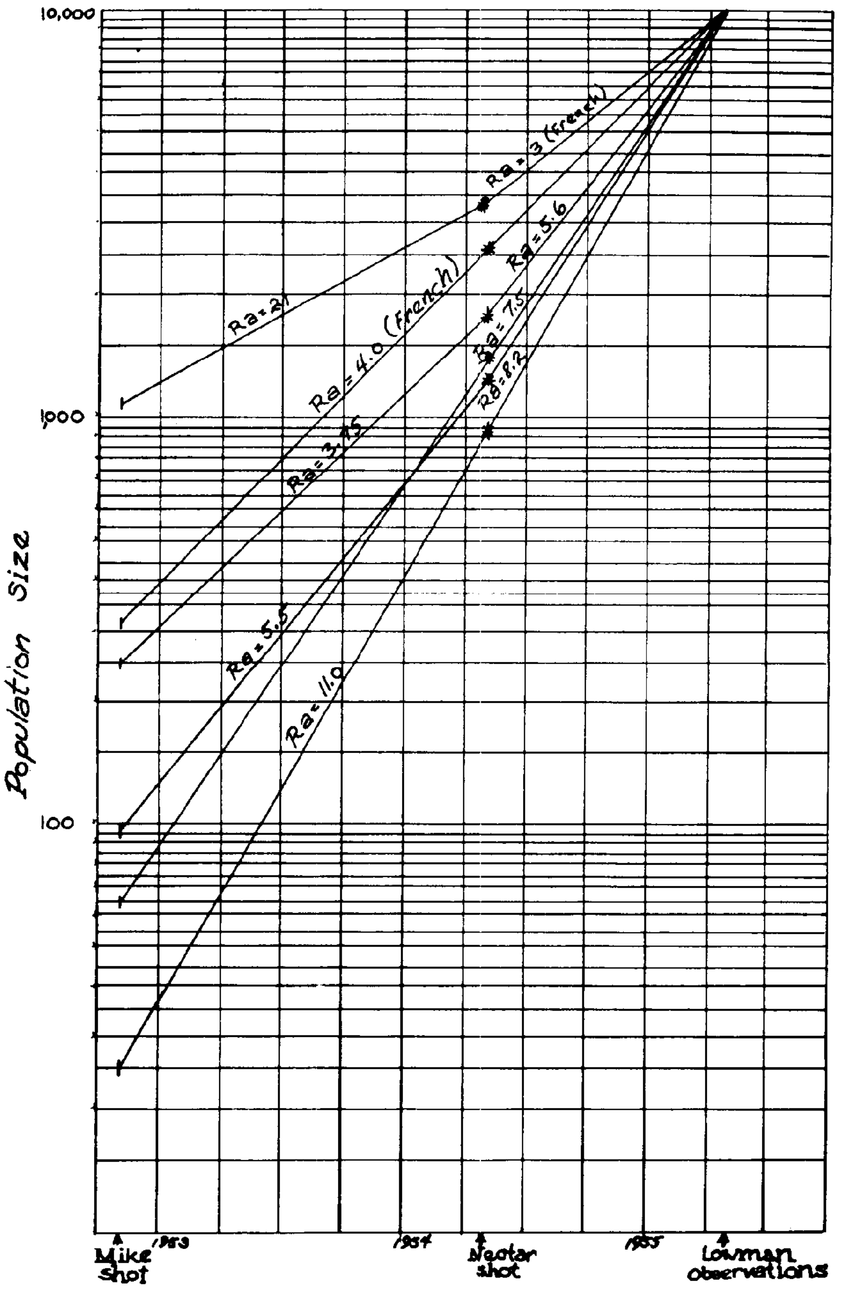

FIG. 5. Initial populations surviving the 1952 "Mike" shot, using several estimates of the annual rate of multiplication (R_a), required to produce a population of 10,000 roof rats in 1955.

1958) is made difficult by taxonomic confusion and lack of specimens. At best, a hypothetical reconstruction can be attempted. Early in the test program at Engebi islet, the Polynesian rat (*Rattus exulans*) was exterminated, probably by heavy surface radiation. Prior to the detonation of a thermonuclear device in 1952, the roof rat (*R. rattus*) had become established on Engebi, and a nucleus survived the heavy initial radiation by being in deep burrows. Calculations show that repopulation by the time of the 1954 and 1955 observations was theoretically possible. The decline of the Engebi rat population from its high density in the mid-fifties probably was a result of a change in the carrying capacity of the environment.

ACKNOWLEDGMENTS

The studies reported here were supported by the Atomic Energy Commission. A contract to the author (AT(11-1)-1485) provided for field work in 1965–1967 and for subsequent data analysis. Field studies in 1964 were conducted while the author was a member of the University of Washington Resurvey Expedition to the northern Marshalls. The facilities of the Eniwetok Marine Biological Laboratory also supported the field work (1964-68). The Laboratory of Radiation Ecology, University of Washington, was of great assistance in providing records, data, and specimens.

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CHRONIC LOW-LEVEL GAMMA IRRADIATION OF A DESERT ECOSYSTEM FOR FIVE YEARS

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Abstract

Populations of vertebrate animals, certain insects, and plants have been studied in three enclosed 8-hectare areas located in the Mojave desert. They were enclosed by a fence to prevent rodents from entering or leaving the study areas. One area was irradiated almost continuously at a dose rate of 80 to 500 mr/hr. Animal populations were examined by capturing, marking and releasing individuals. Plants were examined for growth and for production of leaves, flowers, fruit, and seeds. The life span of the population of pocket mice, *Perognathus formosus*, in the irradiated area was shorter than in the other areas. No difference was detected in the numbers of a small lizard, *Uta stansburiana*, that survived from year to year. Females of a larger but less numerous species of lizard have become sterile in the irradiated area. All vertebrate animals in the irradiated area have received exposures of 1 to 2 r/day. Certain species of plants have produced fewer flowers and fruits in the irradiated area. Plants have received exposures of 4 to 7 r/day. Although wild populations of small mammals are surprisingly sensitive to damage from chronic low-level radiation exposure, they are evidently able to persist under these conditions. There may be certain compensating mechanisms that become operative when the population is subject to radiation stress.

Introduction

Radiation protection as applied to man must consider the individual as the unit of importance. In ecology, the population is the unit of importance. The death or birth of an individual is not necessarily critical to the population, it is merely one of the statistics of which population events are composed. It is essential that over the long term the births in a population equal or exceed the deaths. This is how a population persists. The alternative is extinction. It is the job of the ecologist to analyze the chances of survival for a population, and to evaluate the relative importance of a variety of factors that influence survival of the population.

For several years we have been investigating the effects of chronic low-level radiation exposure on populations of organisms in the desert environment of southwestern United States. This is the type of exposure that a large portion of a population would receive in the event of a nuclear accident or increased industrial use of radiation. The objectives of this study were to evaluate the capacity for increase, or the intrinsic rate of natural increase,

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of vertebrate populations and to examine insect populations and plants for changes in abundance or in growth that could have important effects on the desert community.

Methods

The study area is located in the Mojave desert, in the southern part of the State of Nevada. It is a broad valley that is part of the drainage system leading into Death Valley, which is approximately 100 km away. The elevation is 1070 m. Winter temperatures below 0° C are common, as are summer temperatures above 40° C. Rainfall is approximately 20 cm annually, but 3 to 6 cm may fall during one month, in any month of the year. The vegetation is predominantly desert shrubs, the most numerous being *Lycium andersonii*, *Franseria dumosa*, and *Larrea divaricata*.

In 1962 and 1963 we began intensive studies of the small mammal populations in four circular study areas, each 8 hectares in size. Three of the areas were fenced to prevent movements by small animals into and out of the study areas. One fenced area was provided with a radiation source (French, 1964). At the present time the radiation source contains approximately 30,000 Ci of 137Cs. It is supported 15 m above the surface of the ground in the center of the circular area, and can be lowered into a lead shield from a remote location when investigators enter the area to carry out their studies. It is generally in the raised position 24 hours a day for 26 days each month. When in the raised position, a lead shield of varying thickness below the source partially shields the ground in the region at the center of the study area. The radiation dose rate at ground level near the center of the study area is 12 roentgen per day (500 mr/hr) and near the periphery at 170 m from the source 2 roentgen per day (80 mr/hr). Rodents living in the study area receive an average of approximately 1 rad/day (French *et al.*, 1966) while lizards average about 2 rad/day exposure (Turner and Lannon, 1968).

Animals have been captured, marked and released in the study areas since 1963. The rodent populations were censused at regular intervals. Each rodent had a numbered ear tag or was individually marked by a combination of toe amputations that could be interpreted as a number. The records of these individual rodents were then analyzed for survival, and comparisons made between the irradiated and control populations. The lizards, captured by hand, were marked according to the year in which they were born so that the fractional survival of cohorts could be compared in the irradiated and control areas. Insects and certain other arthropods captured in pit traps were counted and some were individually marked. An attempt was made to evaluate their relative abundance at different times and in the different study areas. The data on arthropods have not yet been reduced and analyzed so results are not included in this report.

Studies of plants included counts of leaves, flowers and fruits produced on selected shoots and measurement of elongation of these shoots of six important species of shrubs, and counts of the numbers of annual plants produced in 199 sample quadrats 0.1 m^2 in each of the study areas, and estimates of the weight of seeds produced by the annual plants. Data on annual plant species are undergoing analysis at this time and are incomplete. Preliminary analyses of the data on shrub species have been completed.

Results

The most abundant species of rodent in the study area is the pocket mouse, *Perognathus formosus*. The life spans of those individuals born in the fenced study areas, and therefore of known age, have been analyzed for comparison of survival of this species in the three areas. In the analysis were included the life spans of 304 animals in Plot A (control), 418 animals in Plot C (control), and 909 animals in Plot B (irradiated). The results (Figure 1) indicate an abrupt decline in the proportion of pocket mice

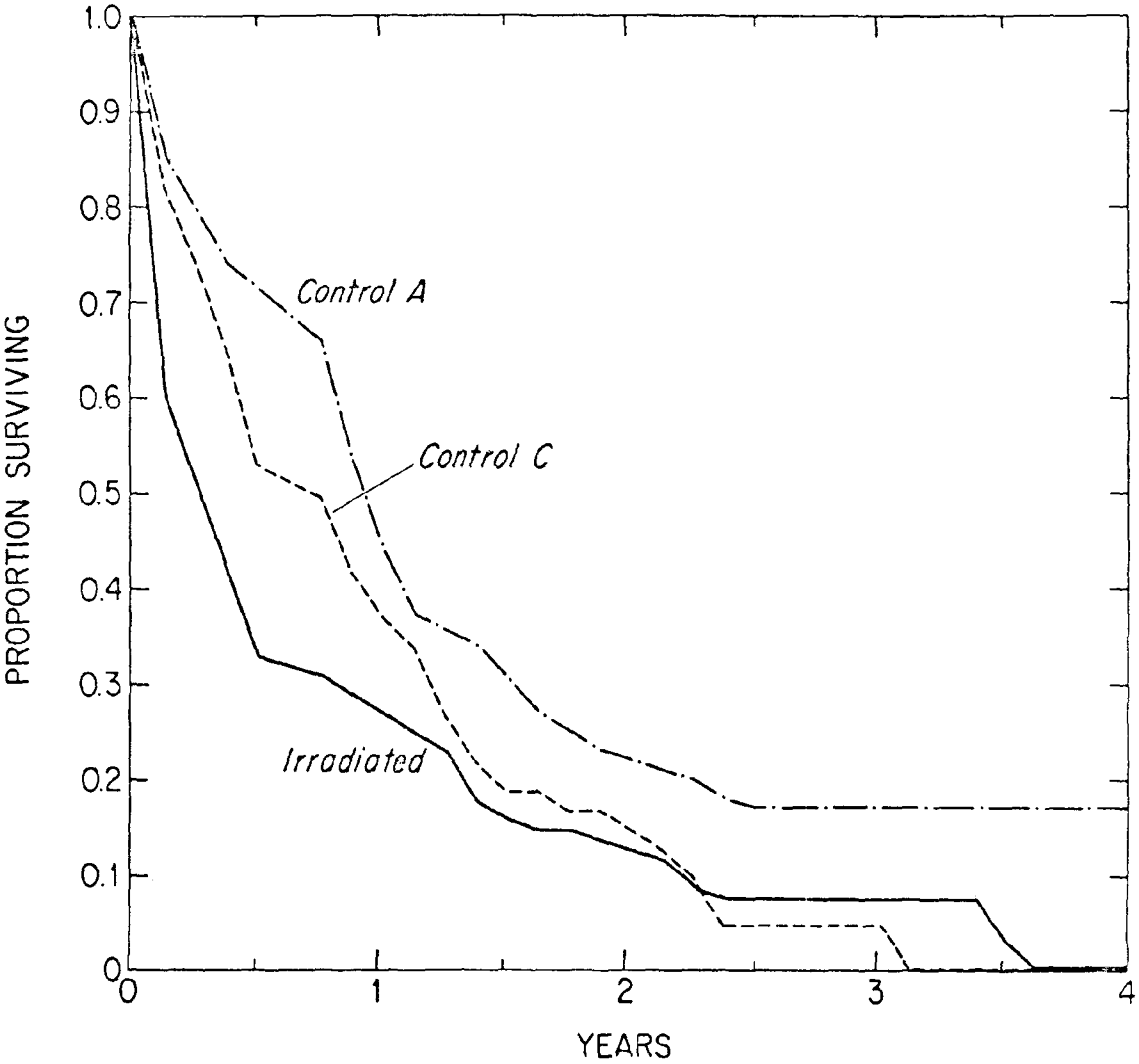

Figure 1. Survival curves for the pocket mouse populations of three fenced study areas in the Mojave desert.

surviving in the irradiated area during the first six months of life. Survival in the control areas was greater during this period. However, those pocket mice that survived irradiation during their early life then demonstrated improved survival over control populations of the corresponding age groups. The average life expectancy for the field populations of Perognathus formosus was approximately 11 months and 7 months for the two control areas (A and C), and 5 months in the irradiated area.

Numbers of lizards were compared by year of age with the Chi-square test. The sex ratios were also compared (Turner et al., 1969). No differences between irradiated and control populations were detected by these methods. However, a larger species of lizard, the leopard lizard, has failed to reproduce for the last two years in the irradiated plot, while reproduction has occurred among populations of this species in the control plots. Female leopard lizards receiving 1 to 2 r/day exposure are sterile after five years of exposure (Turner, manuscript prepared for Nuclear News, 1969).

Comparisons of the growth of six species of shrubs in the irradiated plot and a nearby control area indicated that at least three of the species were significantly different between the two areas (Table 1). The affected species are those with the greatest nuclear volumes. This may be considered as evidence that the differences observed are a result of radiation exposure. The plants were exposed to dose rates of approximately 4 to 7 r/day during the four years considered in this analysis. The significant difference among years is consistent with observations of growing conditions on the desert, which vary widely from year to year.

Discussion

The results of chronic low-level radiation exposure to field populations of small mammals have been corroborated by laboratory studies (French and Kaaz, 1968). Lifetime exposure of deer mice, Peromyscus maniculatus, to 1 r/day in the laboratory reduced the average life expectancy from 28 months in males, and from 22 to 16 months in females. Mortality in the very young age groups is high in irradiated animals, but the adult animals that survive this period of irradiation then survive better than controls of corresponding age groups.

The sensitivity of the mammalian ovary to ionizing radiation is well known (Mandl, 1963; Oakberg and Clark, 1964). We were able to evaluate the effect on fertility of the wild species in the laboratory, but did not succeed in demonstrating this effect under field conditions. The reproductive life span of irradiated deer mice in the laboratory was reduced to 28 months, compared to 40 months in the control animals. Natality, or mean number of female young produced per breeding female, in control deer mice was maximum between 7 and 15 months of age. There followed a steady decline to near zero at 40 months of age. Natality was generally reduced in the irradiated animals and the onset of sterility occurred at an earlier age (French, 1969).

An attempt was made to evaluate natality of the field populations of pocket mice on the basis of the numbers of immature animals that appear in our traps during the breeding season each year. It was not possible to determine the loss of young between the time of birth and the age at which they are able to enter the traps. Comparisons were made between the numbers of embryos in animals sacrificed at a location several kilometers distant from the study areas, and the production of young in the control and irradiated fenced areas. Comparisons for successive years in the control areas were not sufficiently accurate to justify estimation of the potential production of young by the irradiated population.

It is important to recognize that the effects of radiation on different physiological systems of the organism are summed by the population. That is, the effect on life span reduces the number of individuals in the breeding population, and those that remain suffer reduced reproductive potential.

Table 1. Multivariate analysis of Rock Valley shrub growth

SPECIES	ESTIMATED NUCLEAR VOLUME	AMONG YEARS	BETWEEN PLOTS	INTERACTION
Grayia spinosa	128	F = 32.48 **	F = 1.70 NS	F = 1.56 NS
Franseria dumosa	152	F = 42.94 **	F = 1.24 NS	F = 7.26 **
Lycium pallidum	176	F = 15.41 **	F = 0.49 NS	F = 1.09 NS
Larrea divaricata	212	F = 18.43 **	F = 8.46 **	F = 5.78 **
Lycium andersonii	466	F = 41.81 **	F = 3.84 **	F = 7.16 **
Ephedra nevadensis	600-800	F = 13.93 **	F = 3.39 **	F = 4.56 **
Degrees of Freedom for F		12 & 1251	4 & 453	12 & 1251

NS = Not Significant * = significant 5% level ** = significant 1% level

Table 2. Increase in numbers associated with different values for the intrinsic rate of natural increase

INTRINSIC RATE OF NATURAL INCREASE	YOUNG PRODUCED PER FEMALE PER MONTH	MULTIPLICATION PER GENERATION
0.3134	1.37	12.28
0.1897	1.21	5.74
0.38	1.46	18.31
0.32	1.38	11.14
0.21	1.23	6.80

This total summation of events affecting survival of the population is represented by a change in the intrinsic rate of natural increase of the population. The intrinsic rate of natural increase, also called the infinitesimal rate of increase, or r, is the exponent in the familiar equation of exponential growth. It has been used as a measure of the harshness of an animal's environment, although it has been accurately evaluated for relatively few laboratory populations and even fewer natural populations. The value of r for our control laboratory deer mouse population was 0.3134, and for the irradiated population 0.1897. The approximate values of r for the field control populations of pocket mice were 0.38 and 0.32, and for the irradiated population of pocket mice 0.21. There is a marked reduction of the intrinsic rate of natural increase associated with the two groups receiving chronic exposure to ionizing radiation.

The importance of these results lies in their application to understanding the consequences of irradiation of animal populations living in their natural environments. We have demonstrated that wild populations are affected by low levels of exposure, but they still maintain their numbers. This suggests some compensating mechanism that overcomes the detrimental radiation effects.

A change in r also causes a change in the stable age distribution of the population. The stable age distribution is the proportion of animals in the different age groups that would result if the population continued under these conditions for a long period of time. The shift in the stable age distribution results in a greater proportion of the total population in the more fertile age groups, between 5 and 12 months. Some species of rodents, exemplified by laboratory mice and rats, show increased ovulations, implantations and living fetuses, in response to low-level radiation exposure. Our results with wild mice in the laboratory showed a suggestion of this in animals irradiated as adults. If this occurs in wild populations, it would serve as a compensatory mechanism in the classic ecological sense as proposed by Nicholson in 1954.

To help explain the relative importance of the variables we have examined, and to better understand the interaction of radiation and environmental hazards, we have used the techniques of computer simulation to explore the effects on available statistics for wild populations. Survival of Peromyscus in the field is quite different than we observed in the laboratory. Production of young, however, seems to equal that in the laboratory, but the reproductive season under natural conditions is limited. Results of computer population growth indicate that these factors are carefully balanced in nature. Impairment of one or more conditions may have severe consequences for these natural populations.

Radiation will probably have greatest consequences for the population when chance combines it with the most severe periods of a fluctuating environment. We have seen that the rodent population responds to unfavorable periods by failing to reproduce. This results in a declining population, even though survival times may be enhanced during these periods. Both conditions contribute to increase the mean age of the individuals that remain to form the breeding population during the next season. We have also seen that it is the older individuals that are most severely affected by chronic exposures to radiation, in the form of a shortened reproductive life span. It follows that after a series of unfavorable years, an aged irradiated population may have a very much reduced chance of recovery, while a normal population is adapted to withstand such conditions.

To summarize--we are just beginning to have some understanding of how populations of animals are influenced by certain factors in their natural environment, and we are gaining a bit of insight into the ways that radiation exposure can either intensify or modify the effects of environment. Indications are that mammalian populations are more sensitive to damage from chronic low-level exposure than was anticipated. The interaction of some of the environmental factors and population attributes further complicates the picture. The whole problem becomes one of rather complex multivariate analysis. The methods of operations research or systems analysis are proving instructive and have begun to help us unravel the puzzle. Most often, however, the results point to the paucity of really good data available on the factors operating in natural systems.

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RADIATION EFFECTS IN THE SORICIDAE, CRICETIDAE, AND MURIDAE[1]

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Abstract. Effects of acute, ^{60}Co gamma irradiation under controlled conditions in the laboratory were compared in six species of rodents in the Cricetidae, two species in the Muridae, and two species of shrews in the Soricidae. Estimates of $LD_{50\text{-}30}$ for these ten species ranged from 525 to 1069 rads. The most radioresistant species (two species of *Peromyscus*) and the most radiosensitive species (*Oryzomys palustris*) were cricetids. Average survival times of decedents at highest radiation doses (1560–2060 rads) were longer among cricetids (5.6–8.1 days) than in murids (4.4–5.1 days) or soricids (3.5–4.3 days), and interspecific variation was manifested within families. Survival times were longer and LD_{50} estimates were greater in RF-strain, female *Mus musculus* caged alone, than in females caged in groups of five or in males caged either singly or in groups. At high doses, weight losses were rapid and severe in all species, but at lower doses considerable interspecific differences were seen in time of onset and magnitude of weight changes. Other symptoms of radiation damage were conjunctivitis, ataxia, diarrhea, passiveness, cessation of feeding, aggressiveness, and pelage "graying."

Introduction

A relatively narrow range of radiation sensitivity has been reported for most small laboratory mammals. $LD_{50\text{-}30}$ estimates (hereinafter referred to as "LD_{50}") for these mammals usually range from about 300 to 900 rads. Differences in radiosensitivity apparently exist even among strains of laboratory rodents. For example, LD_{50} estimates for 13 strains of laboratory mice irradiated under comparable conditions ranged from 567 to 795 R (Davis *et al.* 1963). Kohn and Kallman (1956) reported differences in LD_{50} estimates (544–665 R) and death rates among four inbred strains and F_1 reciprocal crosses of two of the strains. Estimates of LD_{50} for larger mammals, including man, usually fall between 150 and 600 rads, but such estimations are complicated by significant shielding afforded by tissues, and results must be specified in terms of surface, tissue, or midline doses.

One of the earliest studies of radiation effects in a wild rodent (Kohn and Kallman 1956) reported an LD_{50} of 615 R for feral house mice (*Mus musculus*). Haley *et al.* (1960) showed that survival times and hematological changes in the kangaroo rat *Dipodomys merriami* were similar to responses in laboratory mice and rats, and mortality after 550 R was 93% by the fourteenth day. Comparatively high LD_{50} estimates have been reported recently for other species of wild rodents. Gambino and Lindberg (1964) calculated LD_{50} estimates of 1520 R for the little pocket mouse (*Perognathus longimembris*) and 1300 R for the longtail pocket mouse (*P. formosus*). Chang (1964) reported survival of 9 out of 10 mongolian gerbils (*Meriones unguiculatus*) at 1000 R, and 1 out

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of 10 survived 1500 R. Golley *et al.* (1965) estimated LD_{50} doses of 1125 R for old-field mice (*Peromyscus polionotus*), 1130 R for cotton mice (*P. gossypinus*), and about 1200 R for the eastern harvest mouse (*Reithrodontomys humulis*); their estimate for wild *M. musculus* was only about 700 R. Kellogg (1965) reported an LD_{50} of 1155 R for the cotton rat (*Sigmodon hispidus*). Radioresistant species thus have been reported in the rodent families Heteromyidae and Cricetidae.

Measurements of radiation effects in captive indigenous mammals began at Oak Ridge National Laboratory during the summer of 1964. Need for such research was twofold: (1) radiation responses of various species under standard conditions were required for design of future studies of the effects of irradiation on natural populations, and (2) comparisons of radiation effects in native species and laboratory mammals were necessary for evaluating the applicability of relevant radiobiological data from laboratory animals to wild species. Furthermore, comparisons of radiation effects in various classifications of mammals may help demonstrate to what extent radiation response is related to taxonomic status.

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Materials and Methods

Eight species of indigenous rodents, two species of shrews, and one strain of laboratory mouse were used in these experiments. Species in the family Cricetidae were, in increasing order of weight (names after Hall and Kelson 1959): eastern harvest mouse, *Reithrodontomys humulis*; white-footed mouse, *Peromyscus leucopus*; golden mouse, *Peromyscus nuttalli*; pine vole, *Microtus pinetorum*; marsh rice rat, *Oryzomys palustris*; and hispid cotton rat, *Sigmodon hispidus*. Members of the Muridae used were: house mouse, *Mus musculus*; a laboratory strain (RF) of *M. musculus*; and Norway rat, *Rattus norvegicus*. Species in the Soricidae were: least shrew, *Cryptotis parva*; and short-tailed shrew, *Blarina brevicauda*. The wild rodents were either live-trapped locally or raised in the laboratory; the shrews were all live-trapped. The RF-strain mice were from a colony at the Biology Division, ORNL. All animals were subadults or adults. Animals were caged individually, except for *M. musculus* used in crowding-stress experiments. Nest boxes or cans were provided for all animals except the shrews. Shrews were kept in cages containing chunks ($\sim 1.5 \times 2.2 \times 0.8$ cm) of sod because their fur became oily and matted if soil or a similar material was not available to them.

Food and water were given ad libitum. Temperature was 22 ± 2 C. Humidity for wild species was 50 ± 5%, but humidity was not controllable in the room in which RF-strain mice were kept. The wild species were held in two adjacent and interconnected colony rooms, but the RF-strain mice were kept in a separate room because these laboratory mice, like many inbred strains, are subject to diseases endemic in wild forms. Fluorescent lights were on 12 hr per day. Irradiation and daily inspections were done between 0800 and 1100. Disturbance in the colony rooms was kept to a minimum, because the wild species did not become tame and reacted quickly to sudden movements or noises.

Animals were irradiated in a Gammacell-200 ^{60}Co unit. Dose rate ranged from 828 rads/min at the beginning of the series of experiments to 600 rads/min at the end. Dose was measured with Toshiba low-Z silver metaphosphate glass dosimeters. Glass rods irradiated with known doses at ORNL and the National Bureau of Standards were used as standards. Groups of each species received 0, 500, 690, 875, 1065, 1250, 1625, or 2000 rads. Preliminary estimates of LD_{50} for each species were then made on probit graphs, and additional groups of each species were given bracketing doses around the estimated LD_{50} doses in order to refine the estimates. Final probit analyses were made with the ORNL PROBIT computer program that provided 95% significance limits around the LD_{50} estimates.

Results

Mortality. No significant differences in mortality of indigenous species were demonstrable between sexes and between wild-caught or laboratory-bred animals. The two species of *Peromyscus* were the most radioresistant, with respect to mortality, of all wild species tested; but LD_{50} estimates for most of the other cricetids were not much less and fell within a narrow range of 939–958 rads (Table 1). The rice rat, however, was by far the most radiosensitive of all species tested. Estimates for the two wild murids were slightly lower than estimates for all cricetids except *O. palustris*. The shrews also seemed to be relatively radiosensitive.

The LD_{50} estimate for RF-strain mice caged alone was significantly higher than that for RF mice caged in groups. The difference was primarily attributable to the significant difference between the females of the two groups and not to a difference between males (Table 1). Estimates for the wild male or female *M. musculus* caged together were not significantly lower than estimates for their singly caged counterparts. Although close observations of social interactions were not practical, it was obvious that wild or RF house mice caged in groups quickly set up hierarchies after initial fighting; but individuals were still bitten occasionally, especially on the tail, during the 30-day postirradiation period. However, the mortality among individuals bitten most was not significantly greater than that of animals not bitten or bitten less.

Table 1. $LD_{50\text{-}30}$ estimates for eight species of indigenous rodents, one strain of laboratory mouse, and two species of shrews

Taxon	Total No. Individuals	$LD_{50\text{-}30}$ (rads)	95% SL
Cricetidae			
Reithrodontomys humulis			
♀♀		908	826–1015
♂♂		986	924–1092
Both Sexes	138	947	901–1002
Peromyscus leucopus			
♀♀		1043	976–1111
♂♂		1091	1029–1168
Both sexes	130	1069	1026–1115
Peromyscus nuttalli			
♀♀		1076	970–1206
♂♂		919	743–1020
Both sexes	114	999	918–1071
Microtus pinetorum			
♀♀		1004	890–1168
♂♂		883	772–983
Both sexes	101	939	865–1019
Oryzomys palustris			
♀♀		480	348–551
♂♂		584	435–748
Both sexes	115	525	443–590
Sigmodon hispidus			
♀♀		950	885–1037
♂♂		966	901–1078
Both sexes	123	958	914–1013

Table 1. Continued

Taxon	Total No. Individuals	LD$_{50-30}$ (rads)	95% SL
Muridae			
Mus musculus			
Wild			
1 in cage			
♀♀		802	701–880
♂♂		851	774–920
Both sexes	140	827	772–877
5 in cage			
♀♀		799	659–928
♂♂		829	751–900
Both sexes	100	811	755–861
RF strain			
1 in cage			
♀♀		1053	973–1145
♂♂		888	784–979
Both sexes	136	984	894–1080
5 in cage			
♀♀		736	581–860
♂♂		837	703–976
Both sexes	125	780	694–860
Rattus norvegicus			
♀♀		795	711–918
♂♂		949	833–1069
Both sexes	101	867	739–989
Soricidae			
Cryptotis parva			
♀♀		785	644–956
♂♂		998	473–2106
Both sexes	40	837	634–1174
Blarina brevicauda			
♀♀		791	662–945
♂♂		767	593–981
Both sexes	40	780	667–904

Survival Times. Postirradiation survival times of decedents were fairly predictable for each species at high doses (1200–2060 rads); but results varied more at lower doses – variability at those doses depending in large part on relative radiosensitivity of the species. No significant differences in the wild species were apparent in survival times of sexes or in the wild-caught or laboratory-bred specimens. Survival times of most cricetids at the highest doses were relatively long in comparison to the other families (Fig. 1). *Peromyscus leucopus*, the most radioresistant species (in terms of LD$_{50}$), had the shortest survival times of the cricetids. On the other hand, *P. nuttalli*, another radioresistant species, exhibited the longest survival time of all species. The most radiosensitive species, *O. palustris*, had the second shortest survival times of the cricetids. The wild murids caged alone did not survive long at the highest doses. Survival

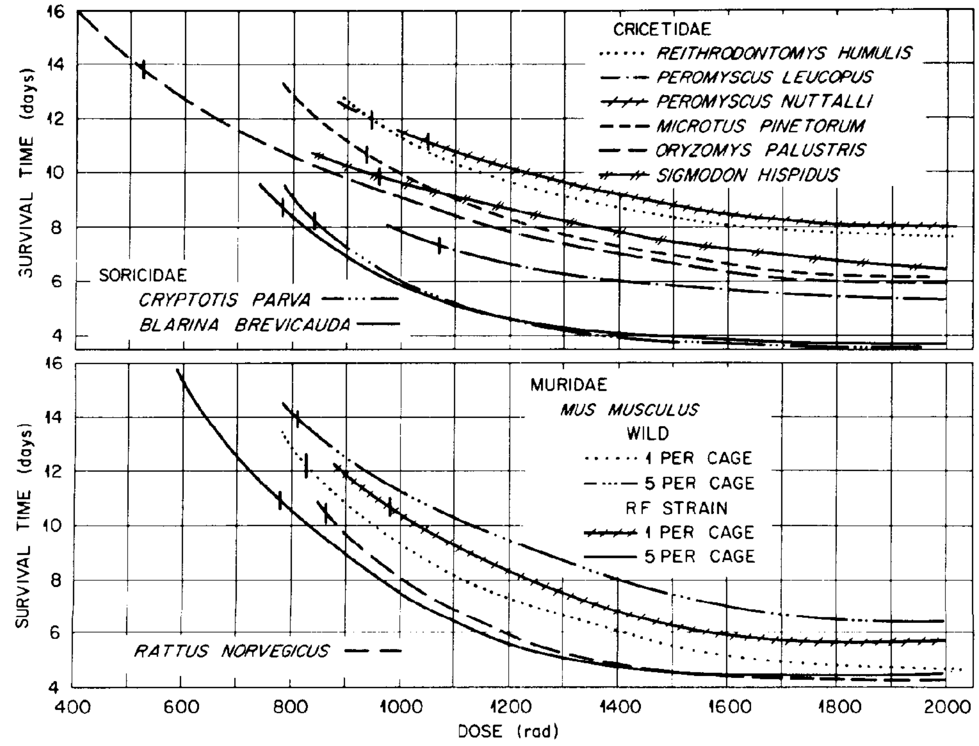

Fig. 1. Survival times of rodents and shrews. Curves are projected only to lowest doses at which three or more individuals died. Vertical bars indicate LD$_{50\text{-}30}$ estimates.

times of the soricids also were relatively short. At highest doses (1560-2060 rads), where times were almost identical for each species, average times ranged from 3.5–4.3 days for the soricids, 4.4–5.1 days for the murids, and 5.6–8.1 days for the cricetids.

Species size was not related to survival times, even within families. In the Cricetidae, the two *Peromyscus* were virtually the same size; but, as pointed out, one species had the longest and the other the shortest survival times in the family. The tiny *R. humulis* survived longer than the rat-sized cricetids, but the pine vole lived about as long as the rats. Similarly, house mice usually lived longer than the much larger Norway rat, but the short-tailed shrew, four or five times larger than the least shrew, lived about as long.

Survival times for grouped RF mice were considerably less from about 900–2060 rads than for solitary RF mice (Fig. 1). However, this difference was attributable to the females caged alone, which had consistently longer survival times than did males caged alone; times for males caged alone were not consistently different from times of either sex caged together. On the other hand, survival times for wild *M. musculus* caged alone were shorter than times for grouped wild house mice, in spite of the fighting that occurred among the grouped mice. No consistent difference in survival times of the wild mice at the highest doses was seen between sexes caged alone or in groups, but times of each sex caged singly were consistently less than times of the respective sexes caged together.

Weight Changes. Postirradiation weight losses at all doses for all species at death ranged from 9–38%, and differences in extremes for each species ranged from 6–24%. Considering only the three groups of highest doses, weight losses of all species were 14–34%, and differences in extremes for each species reduced to 2–10% (Table 2). Animals losing most weight (average) at these highest doses were: RF mice caged singly, 33%; RF mice caged together, 31%; wild *M. musculus* caged together, 31%; and *P. nuttalli*, 29%. Species showing least loss at the highest doses were *P. leucopus*, 16%; *R. humulis*, 17%; *O. palustris*, 19%; and *R. norvegicus*, 20%. Differences in weight loss among species were not ascribable to taxonomic status, at least at levels under consideration, and no relation with species size was discernible.

Weight changes of control animals of each group were plotted in terms of percent weight change from day 0. Of the four irradiated groups losing most weight, controls of both groups of RF mice and the *P. nuttalli* gained weight steadily during the month following day 0. Controls of the other irradiated group exhibiting considerable weight loss (wild *M. musculus* caged together) gained weight until about day 15, after which average weight dropped to about the same level as weight at day 0. Controls of three species (*P. leucopus*, *O. palustris*, and *S. hispidus*) lost about 5% of their weight during the first week, then gained weight during the subsequent three weeks, but did not recover the loss. *M. musculus* caged alone, *R. norvegicus*, and *M. pinetorum* lost approximately 5% during the first week, but gained slowly to near or slightly above original values.

Table 2. Weight losses at death of rodents and shrews in selected dose groups. Weights of control groups are averages at day of irradiation. Values for irradiated groups are percent of weight remaining for the respective groups from day of irradiation.

	Control Weights (g)	Dose (rads)				
		860–930	1030–1100	1200–1300	1560–1660	1890–2060
Cricetidae						
Reithrodontomys humulis	8.3	78.3 ± 3.44	80.3 ± 3.45	82.4 ± 3.37	81.1 ± 2.89	85.2 ± 4.00
Peromyscus leucopus	19.8	*a*	78.5 ± 4.30	84.5 ± 2.82	84.9 ± 2.59	83.3 ± 2.24
Peromyscus nuttalli	26.6	83.8 ± 3.82	80.0 ± 3.63	69.3 ± 2.34	72.0 ± 2.04	72.9 ± 2.26
Microtus pinetorum	30.6	79.2 ± 2.55	85.4 ± 4.33	70.9 ± 2.66	75.1 ± 2.97	78.6 ± 2.04
Oryzomys palustris	52.1	79.7 ± 1.72	78.8 ± 1.51	77.8 ± 0.98	79.7 ± 2.07	85.6 ± 1.29
Sigmodon hispidus	118.2	81.6 ± 4.36	80.9 ± 1.96	78.8 ± 3.21	75.8 ± 1.87	77.6 ± 1.54
Muridae						
Mus musculus						
Wild						
1 per cage	18.7	77.5 ± 3.53	68.2 ± 2.82	74.7 ± 3.27	76.9 ± 1.93	82.3 ± 2.01
5 per cage	15.4	76.0 ± 3.13	71.1 ± 1.60	71.5 ± 2.27	69.6 ± 3.79	65.6 ± 1.77
RF Strain						
1 per cage	29.2	69.8 ± 3.67	61.9 ± 1.83	68.2 ± 1.68	66.6 ± 1.90	67.4 ± 1.66
5 per cage	30.4	73.2 ± 1.92	72.4 ± 3.32	69.2 ± 2.52	68.0 ± 1.90	69.6 ± 2.07
Rattus norvegicus	238.7	72.0 ± 2.00	74.2 ± 1.41	77.8 ± 2.01	81.3 ± 1.75	80.3 ± 1.41
Soricidae						
Cryptotis parva	3.6	79.0 ± 0.98	76.1 ± 2.63	71.8 ± 4.89	78.6 ± 1.17	76.5 ± 1.52
Blarina brevicauda	16.5	83.8 ± 4.81	90.8 ± 2.65	67.0 ± 3.84	77.4 ± 5.25	76.4 ± 0.37

[a] Fewer than three animals died.

R. humulis was the only species in which controls increased in weight (106%) during the first week and then lost weight slowly until, during the last week, average weight loss was about 4%.

Other Radiation-Effects Symptoms. Symptoms in irradiated species included conjunctivitis, ataxia, passiveness, cessation of feeding, diarrhea, aggressiveness, and "graying" of hair. Appearances of the first four symptoms usually, not invariably, were followed by death, but death was not always preceded by all of these symptoms. Conjunctivitis caused "watering of the eyes," and in many cases the exudate matted the eyelids together so that animals could not see. Ataxia in most species was sometimes present for several days and was characterized by uncoordinated and slow movements. Ataxia in shrews, however, usually was not pronounced until a few hours before death. Passive animals of all species in a terminal stage exhibited the "righting reaction" until they were moribund. Cessation of feeding ordinarily was gradual, but little or no food usually was ingested for 2–3 days before death. In some cases, even shrews ate little or nothing for 1–2 days before death, suggesting a drastic slowing of metabolism in these animals, which normally must ingest a considerable amount of food each day. Diarrhea was noted mostly at higher doses, and in a few cases blood was present in the discharge. Increased aggressiveness occasionally appeared in some individuals. This change in behavior was particularly noticeable in *R. humulis* and *P. nuttalli*, species which characteristically cowered in their nests during inspection and were relatively slow-moving. Irradiated individuals sometimes became aggressive, sat up on their hind legs, and attacked fingers or other objects inserted into their nests.

Pelage graying is one of the most striking consequences in mammals receiving substantial but sublethal doses of irradiation. Because of colony-space limitations, graying sequences were followed in only a few specimens of *B. brevicauda*, *P. leucopus*, *S. hispidus*, and *M. musculus*. In most of the individuals observed, development of graying was similar to that shown for laboratory animals; i.e., unpigmented hair replaced pigmented hair when the animals molted. Chase (1949) showed that response (percentage of white or mosaic hairs) was proportional to dose and that response was much greater in resting follicles than in growing follicles. Graying in *P. leucopus* is shown in Fig. 2. The pattern of graying shown is similar to that seen in all rodents examined; i.e., graying began on the head, appeared next on the dorsum and/or sides, and progressed posteriorly. However, graying time varied between individuals. In Fig. 2, note that graying progression was less advanced in No. 1510, 135 days postirradiation, than in No. 1514, 105 days after irradiation with the same dose. A different pattern of cutaneous response was observed in *B. brevicauda*. Three of these shrews developed erythema and epilation of their backs during the month following irradiation. One died 28 days after 875 rads, and another died after 142 days (690 rads) with chronic, ulcerative dermatitis and abscesses associated with the epilated area. Unpigmented hair appeared in the two epilated areas of the remaining shrew (875 rads) and other patches of unpigmented hair developed later, giving the animal a piebald appearance (Fig. 3). Two other shrews, one receiving 780 rads and the other 690 rads, exhibited no graying after 250 and 255 days, respectively. Hamilton (1940) was of the opinion that molt in *B. brevicauda* did not proceed in any conventional manner and that molting could occur in a few days.

Discussion

Intraspecific and interspecific comparisons of radiation effects in captive mammals require careful consideration of a host of factors known to influence radiation responses. We found differences in mortality, survival times, and weight changes among our experimental species, which were confined, irradiated, and handled under similar conditions. However, we do not know to what degree captivity stresses and other influeces may have modified these responses in each species. Specimens of wild species, even those born in the laboratory, cannot be regarded as "domesticated" and react to handling and caging differently from conventional laboratory animals. Sex, age, temperature, diseases, parasites, fatigue, and diets are but a few of the factors known

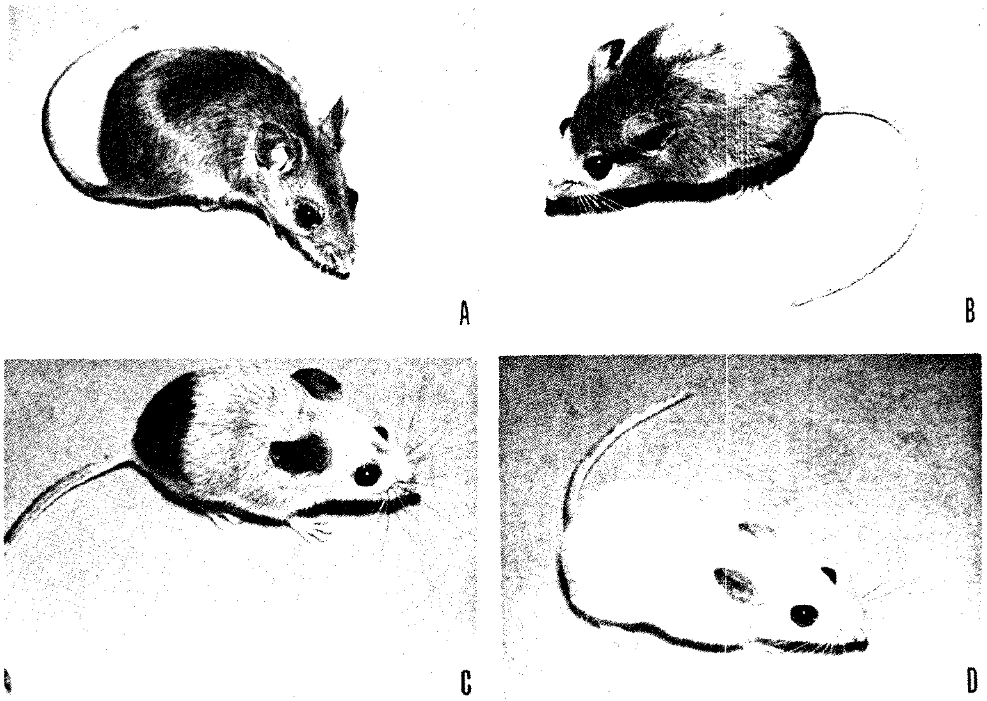

Fig. 2. Graying in *Peromyscus leucopus* irradiated with 1070 rads. A. Unirradiated control. B. No. 1510, 135 days postirradiation. C. No. 1514, 105 days. D. No. 1514, 215 days.

to influence radiation-effects syndromes, and it would be naive to assume that interactions of such factors with radiation were identical in all species.

Dose rate must be considered carefully in intraspecific and interspecific comparisons of mortality, survival times, and other irradiation responses. At dose rates much below 100 rads/min, increasing amounts of radiation were required to produce 50% mortality in mice in 30 days (Lindop and Rotblat 1963). Dacquisto (1960) found that, even at 3 or 30 R/min, LD$_{50\text{-}30}$ estimates differed in laboratory mice (743 vs 650 R, respectively) and laboratory rats (684 vs 498 R, respectively). Data by Logic *et al.* (1960) for Sprague-Dawley *R. norvegicus* are particularly instructive on this point; at dose rates of 0.176, 0.487, 3.41, 55, and 474 R/min, their LD$_{50}$ estimates were 2110, 1885, 1277, 1044, and 908 R, respectively. Consequently, comparisons of our LD$_{50}$ estimates with the higher estimates of Golley *et al.* (1965) and Kellogg (1965) for certain species should be made with caution. Dose rates in their experiments were 1.8–25.9 rads/min as compared with our 600–828 rads/min. Similarly, the radioresistance reported by Chang (1964) for *Meriones unguiculatus* should be viewed with knowledge that his dose rates were 7.3–9 and 22 R/min (dose rates given by personal communication). The LD$_{50}$ estimates of 1520 and 1300 R for two pocket mice, *Perognathus longimembris* and *P. formosus*, respectively, were obtained at a dose rate of 102 R/min (Gambino and Lindberg 1964). It appears that these pocket mice are comparatively radioresistant, even though another heteromyid rodent, *Dipodomys merriami*, was relatively radiosensitive (Haley *et al.* 1960). All cricetids, except *O. palustris*, examined so far seem to be more radioresistant than all murids or soricids studied to date.

Heterozygosity has been suggested repeatedly as a cause of increased radioresistance. Rugh and Wolff (1958) suggested that heterosis resulted in increased survival of C$_{57}$ × CF$_1$ hybrids, compared with survival of the pure strains. Work by Kohn and Kallman (1965) with four inbred

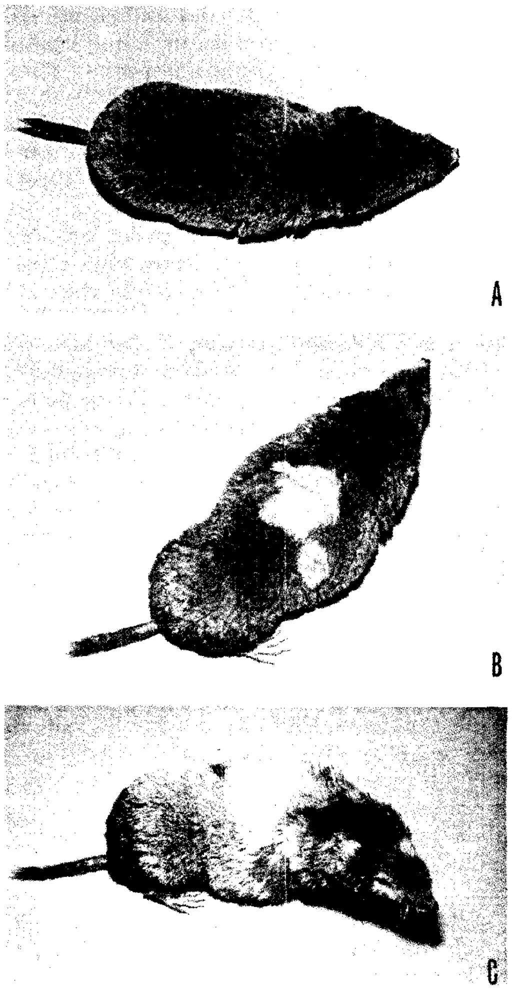

Fig. 3. Graying in a *Blarina brevicauda* (No. 1531) irradiated with 875 rad. A. Unirradiated control. B. 92 days postirradiation. C. 202 days postirradiation.

strains of mice and reciprocal crosses of two of the strains also indicated increased radioresistance in the hybrids, but their LD_{50} estimate for wild *M. musculus* was lower than all except the radiosensitive BALB/c strain. Of eighteen strains used at ORNL, three were hybrids and were among the most radioresistant of the strains (Davis *et al.* 1963). No significant difference is apparent between LD_{50} estimates of Golley *et al.* (1965) for wild house mice and a strain of laboratory mice from crosses of four other strains. In our experiment no significant difference was seen between RF-strain and wild *M. musculus* males, and the RF females caged alone were more, not less, radioresistant than male or female wild house mice. It may be unfair to compare results for wild species with data for domesticated inbred and hybrid animals because of possible differences in captivity stresses between wild and domesticated animals.

Rajewsky (1954) depicted a sigmoid curve for survival times of white mice irradiated at doses from 250 to 200,000 R and pointed out that this dose-survival curve can be divided into several dose ranges in which different mechanisms of damage may predominate. It is well known that acute-radiation death is not assignable to damage of one system or organ alone, but that radiation-death syndromes actually result from complex organismal responses. However, the multiple events preceding early irradiation deaths after doses from about 500–10,000 rads usually follow more or less characteristic patterns, and these syndromes seem to be related primarily to cellular damage in hemopoietic and gastrointestinal systems (Quastler and Zucker 1959). Rajewsky (1954) also showed that adrenal and pituitary glands are of decisive importance in terms of dose dependence and survival times in this dose range.

The curvilinear nature of survival-time curves for our species indicates that survival times in the 1560–2060 rad range are on the first part of the plateau wherein mortality times are independent of dose. The cricetids exhibited relatively long survival times in this dose range, while the wild murids and shrews had relatively short survival times. Since the gastrointestinal-death syndrome begins to predominate in this dose range, it may be that basic differences exist in cellular differentiation or proliferation rates in the GI tracts of these families. The ascending limbs of our curves toward the lower doses cannot be projected very far beyond the LD_{50} estimates because of the small number of animals dying and the increasing variability of survival times in these few animals, but it is apparent that all LD_{50} estimates lie in the dose ranges where the hemopoietic-death mode predominates in most laboratory rodents. Reductions in lymphocyte number, erythrocyte number, hemoglobin concentration, and hematocrit percentages were much more severe in the radiosensitive *O. palustris* than in *P. leucopus*, *S. hispidus* and *M. musculus* after whole-body, acute, gamma irradiation with 200 and 400 rads (Dunaway *et al.* 1967).

Michaelson and Odland (1962) suggested that radiation recovery half-time and leukocyte depression time are inversely related to size of mammal and to metabolic rate. In our study, body size and metabolic rate, even within families, were not related to survival time, mortality, weight change, or other radiation effects observed.

Differences in patterns of weight changes in the various species may reflect, at least in part, differences in captivity stresses and/or fat accumulation. For example, controls of the two irradiated groups that lost most weight (RF-strain *M. musculus* caged alone and in groups) consistently gained weight. Controls of wild, singly caged *M. musculus* also gained weight, at least during the first two weeks, and irradiated individuals lost considerable weight. The RF mice have been domesticated for many generations, of course, and house mice commonly live in proximity to man; such animals may experience less captivity stress. Irradiated golden mice were the fourth group that lost much weight; controls of these animals were slow-moving, generally inactive, and gained weight. Although accumulation and loss of stored fat was not measured in this experiment, it may be that much of the weight loss in irradiated animals reflects fat loss.

Furthermore, it is possible that survival time of fat animals may be longer than for animals with little fat. Obesity was markedly more common in golden mice than in any other species, and *P. nuttalli* had the longest survival times of all species tested. Ershoff (1960) found considerably shorter survival times in mice on low-fat diets compared with mice receiving rations supplemented with cottonseed oil, desicated liver, or methyl lineolate.

Results of experiments in which animals are caged singly or in groups should be evaluated carefully. Raventos (1955) reported a cage effect but found no significant differences in mortality between irradiated mice caged singly and those caged together, in contrast to our higher LD_{50} estimates for female RF mice caged alone and the similar results of Hahn and Howland (1963) for female Wistar rats. However, designs of crowding-stress experiments have varied. We kept randomly selected individuals together (5 per cage) for one week prior to irradiation and did not redistribute survivors after irradiation to maintain group numbers. Hahn and Howland used animals from a commercial supplier, assigned 1, 2, 4, or 6 randomly selected rats per cage 4 to 5 days before irradiation, and recombined survivors to maintain constant numbers per cage. Raventos (1955) used mice from a supplier, put one or ten individuals in a cage, daily shuffled groups of mice caged together, did not shuffle other groups of mice caged together, and did not recombine survivors. He warned, however, that "... there were construction differences between the individual and the group cages which must have produced environmental differences."

It is well known that, in general, less fighting occurs among litter mates of the same sex kept together than between groups recently combined from different litters; and fighting is more severe in a group during establishment of a social hierarchy than after dominance-subordinance relationships have been established. Brown and White (1958) showed that mortality is less and survival times longer in rats fatigued and then irradiated than in rats irradiated and then fatigued or even in rats receiving no treatment except irradiation. Even sexual activity caused drastic increases in mortality of irradiated mice (Rugh and Grupp 1960). Consequently, fighting or other social stresses prior to or after irradiation may affect the outcome of crowding-stress experiments. Temperature may be important in such experiments, but laboratory or colony-room temperatures are not specified in many reports. At temperatures below thermoneutrality for a given species, grouped animals may be at an advantage because of better heat retention in huddling groups. Shipman and Cole (1966) indicate the care that must be exercised in evaluating modifications of radiation effects by environmental stressors: "... the constellation of nonspecific neuroendocrine reactions to a stress which Selye has termed the adaptation syndrome, is very complex, and is not easily amenable to quantitative measurement; it is likely that the 'degree of stress,' and its timing relative to radiation exposure, are critical determinants as to whether the elicited response is radioprotective, or indeed, deleterious."

Radiation effects such as conjunctivitis, ataxia, agressiveness, and pelage graying probably would make affected small mammals more vulnerable to predation. This aspect may be almost academic, since doses of the magnitude required to produce these effects may sterilize these animals. On the other hand, selective removal of such sterilized individuals by predators may reduce intraspecific competition and predator pressure on the less-affected members of the populations.

The comparative radiosensitivities reported here for wild small mammals in the laboratory are useful for planning field experiments, and certain findings may be provocative to laboratory radiobiologists. An observation that arises from comparisons of relevant radiobiological and radioecological research is that radiobiologists need to be aware of pertinent ecological information (e.g., population-density studies) and radioecologists should be cognizant of pertinent radiobiological findings (e.g., dose-rate effects). Extensive ecological and radiobiological knowledge is available; and perhaps such information can be joined for rough, first-approximation predictions, but only research with actual populations in irradiated environments will provide data needed for predicting consequences of ionizing radiation in large ecological systems. Successful descriptions of holoecological responses to irradiation will require: (1) natural environments subjected to controllable or uniform radiation, (2) adequate laboratory and field instrumentation, and (3) concerted, cooperative efforts by large teams of investigators representing many disciplines. These requirements are yet to be fulfilled.

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EFFECTS OF GAMMA IRRADIATION ON POPULATIONS OF SOIL INVERTEBRATES

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Abstract. Invertebrate animals living in soil or on moist plaster of Paris were irradiated with gamma rays from a cobalt source. Soil samples and cultures were adequately replicated and radiation doses ranged from 10 krads through 25, 50, 100 and 200 krads. The animals in culture included representative Oligochaeta, "Myriapoda," Acarina, Collembola and Insecta. Susceptibility to radiation varied greatly both between and within groups. Oribatid mites were most resistant, surviving up to 80 days after exposure to 200 krads; and isopods, which were most susceptible, were all dead 60 days after exposure to 10 krads. There was excellent correlation between activity and susceptibility to radiation.

Mortality/time curves were not linear even on a probit scale but were usually distinguishable into an initial steep curve and a shallow secondary one. Radiation dosages were positively correlated with percentage mortalities but not in a simple logarithmic or probit relationship.

Populations of all main groups of invertebrates in soil samples were regularly counted for three months after irradiation. Most decreased in numbers sigmoidally with time, but a few species eventually multiplied after a small dose of radiation, probably due to greater susceptibility of predator than prey. Animals were usually more susceptible to irradiation in cultures than in soil.

Introduction

The amount of environmental pollution by radioactive wastes and fallout increases annually. As the industrial use of atomic power becomes more widespread, the problem of radioactive waste disposal intensifies, and it becomes more likely that terrestrial ecosystems may become further contaminated and changed. At present, high level wastes (up to 500 curies of radioactivity per gallon of water) are usually discharged into the sea, but low level wastes (up to 100 millicuries per gallon) which come from factories, laboratories or hospitals may reach sewage beds or be otherwise dispersed into the soil. Smaller quantities of radioactivity reach the soil from aerial fallout or from decomposing plant and animal tissues which contain isotopic residues. With all these potential sources of terrestrial radioactivity, studies of the effects of radiation on the soil ecosystem seem essential. Soil invertebrates have important roles in this system by breaking down plant material and mixing it intimately into the soil and turning over and aerating the soil as they tunnel through it.

Investigations into the effects of radiation on invertebrate animals have been mainly confined to a few insect orders. Most studies have had secondary aims of using gamma radiation to control stored product pests, particularly beetles; to study its genetic and physiological effects on several test insects, especially *Bracon* and *Drosophila*; or to determine suitable dosages to sterilize economic insects which are then released to interfere with the mating and reproduction of natural populations. An adequate review of some of this work was made by O'Brien and Wolfe (1964). All of these studies have concerned the effects of radiation on collections of individuals of a single

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species, and few of the insects tested spend any part of their life in soil. Auerbach *et al.* (1957) did preliminary work on the effect of radiation on Collembola population growth in culture, but the only study of the effects of radiation on natural populations of invertebrates was that by Auerbach (1958) who indicated the possibility that treatment of an entire community with radiation may cause increase in numbers of some species, probably because a predator may be more susceptible to the radiation than its prey. Such increases in numbers of prey species have been shown to result commonly from the use of many pesticides in soil (Sheals 1956, Edwards 1960, 1965a, 1965b). To analyze such complex effects it is necessary to investigate the effects of the biocide both on single-species cultures of animals and on whole communities. The scope of the present work is to do this for a range of soil invertebrates. Furthermore, there have been no studies that have compared the effects of a range of doses of gamma radiation on many different invertebrate taxa simultaneously, to determine their relative susceptibility to the radiation.

Methods

The experimental site at Rothamsted Experimental Station, England, was a mixed woodland soil rich in organic matter, which contained unusually large numbers of invertebrates representative of most of the groups which normally inhabit soil. The invertebrates were exposed to gamma irradiation either as mixed populations in intact soil cores or in single-species cultures kept on moist plaster of Paris. Soil cores for direct irradiation or for providing animals for the cultures were taken with a two-inch diameter sampling tool to a depth of 6 inches and put into aluminum cans slightly larger than the samples. The animals were extracted for the cultures as soon as possible in Tullgren funnels and collected in small vials with a layer of moist plaster of Paris on the bottom. The Tullgren funnels which were aluminum and steep-sided had soil containers six inches in diameter and four inches deep. One soil sample half-filled a soil container and the heat source above it gave a temperature gradient through the soil from 30 to 35 C at the top to 20 C at the bottom of the sample. Representative species of three families of Acarina and one each of Collembola, Diptera larvae, Coleoptera adults, Diplopoda, Isopoda and Oligochaeta (see Appendix) were chosen from the samples and kept in cultures on plaster of Paris. The microarthropods were cultured in vials one inch in diameter and one inch deep with a layer of moist plaster of Paris on the bottom. The larger invertebrate cultures were in petri dishes two inches in diameter also containing a layer of plaster of Paris. In the enchytraeid cultures, a thin moist layer of leaf litter was placed on the surface of the plaster, and one hundred and ten animals were put into each culture vessel. The other cultures each contained ten animals and small yeast pellets were added periodically as food for Collembola, Diplopoda, Isopoda and saprophagous Acarina.

Ten intact soil cores were taken close together from an area of uniform soil marked out into 12 adjoining quadrats each large enough to provide 60, two-inch diameter soil cores. Within each quadrat, samples were taken in six sets of ten, each set distributed evenly over the area. The samples, in aluminum cans were stored overnight at 5 C and irradiated the next day in a large package-irradiation plant at the Wantage Research Laboratory (AERE), Wantage, Berkshire, England. The source contained 300,000 curies of ^{60}Co in a rectangular frame, approximately seven feet long by two feet high with a gamma-dosage of 0.117 megarad per hour at a distance of one foot from the source. Samples and cultures were stacked in rows one above the other parallel to, and about one foot from the source and the doses of 10, 25, 50, 100, and 200 kilorads were varied by extending the times of exposure from about five to 100 minutes.

Five batches of single-species cultures each consisting of six cultures of wood lice, five cultures of oribatid and parasitid mites, three cultures of fly larvae, beetle adults and enchytraeid worms, and two cultures of uropod mites and millipedes were exposed to the five doses of radiation. One batch was not irradiated. At the same time five batches of soil samples consisting of ten samples from each of the 12 quadrats were irradiated with the five different radiation doses, within the aluminum cans in which they were collected. One similar control batch of samples was not irradiated although it was taken to the packaging plant with the other samples so that it had the same temperature changes as the irradiated ones.

The cultures and soil samples were kept in a constant temperature room at 15 C. All cultures were examined daily for the first week, and thereafter at intervals of 2 to 3 days, and all dead animals were counted and removed. Because the counts were spread over two months, mortality in the controls was inevitable. It was moderate for the Enchytraeidae, Isopoda and Oribatidae but heavy in the Parasitidae where there was much cannibalism although animal food was provided. After two months enough control animals of most groups had died to make further observations unprofitable.

The batches of soil samples were re-sorted into their original quadrat groupings so that every group contained five sets of ten samples each treated with one of the irradiation doses. Ten samples had not been irradiated. Every few days one group of samples was taken from the constant temperature room and placed in Tullgren funnels. These times were 1, 4, 10, 13, 19, 29, 42, 55, 62, 69 and 76 days after the samples were irradiated. The extraction of all the animals into vials containing 70% alcohol and 5% glycerine took three days. They were stored until they could be examined and categorized under the binocular microscope.

Results

The cumulative mortality counts in the cultures are summarized in Figs. 1 to 9; standard errors are not included to avoid confusing the graphs. The full data from the soil samples that were irradiated intact were too extensive to include here, but Table 1 gives the numbers of the various groups of invertebrates surviving 42 days after irradiation, expressed as a percentage of the control numbers. Table 2 lists the times taken for *all* the animals in ten soil samples to die, after exposure to 200 kilorads of radiation. These figures are approximated to the nearest ten days and are intended to show only the relative susceptibility of the animals to a large dose of radiation. The reason is that samples were examined at only 7 to 10 day intervals giving a range of about ±3 to 5 days in the estimate. Furthermore the Tullgren method of extraction imposed two limitations: firstly, animals which were not killed but only paralyzed would not emerge from the soil samples, and so were recorded as dead. Secondly the times quoted represent the intervals between irradiation and when the samples were placed in Tullgren funnels; but it takes three days for all animals to be extracted from a soil sample. So, with the majority leaving after 36 hours, this is likely to be

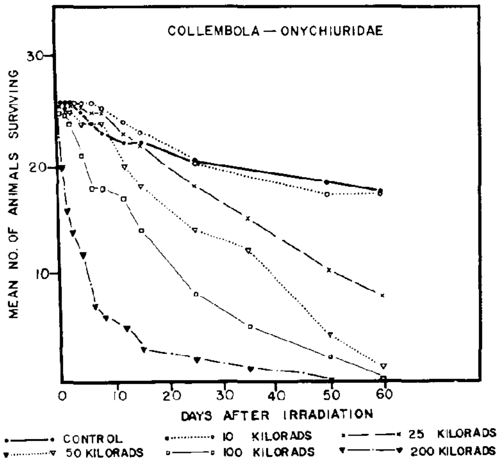

Fig. 1. Effects of different doses of gamma radiation on invertebrates in culture.

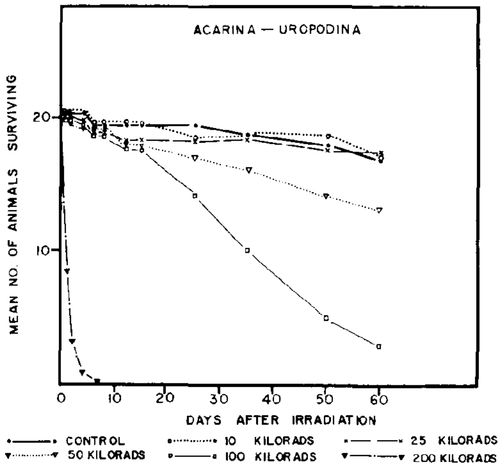

Fig. 2. Effects of different doses of gamma radiation on invertebrates in culture.

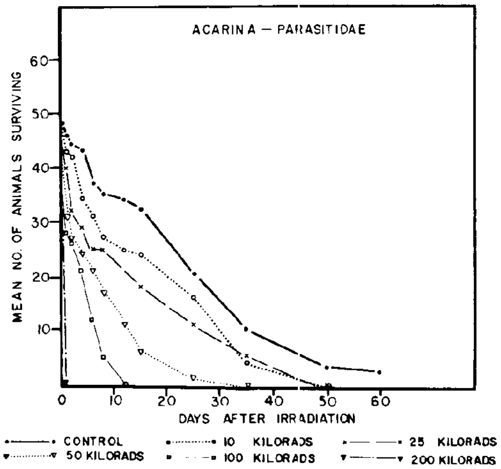

Fig. 3. Effects of different doses of gamma radiation on invertebrates in culture.

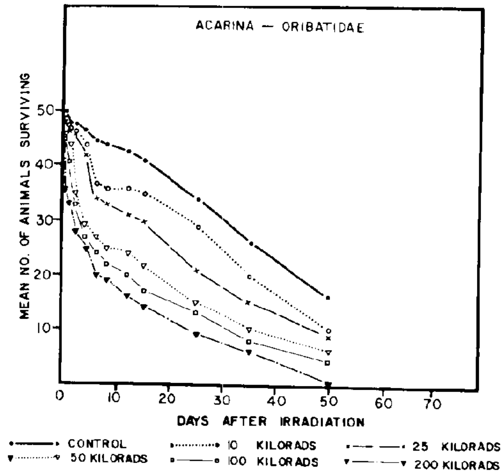

Fig. 4. Effects of different doses of gamma radiation on invertebrates in culture.

Table 1. Percentage survival in soil 42 days after gamma irradiation

Taxonomic Category	Percentage Surviving After 42 Days				
	10 kr	25 kr	50 kr	100 kr	200 kr
Nematoda	48.0	37.5	37.5	16.7	6.3
Lumbricidae	100.0	72.8	41.9	13.6	
Enchytraeidae	41.5	47.7	52.0	10.4	
Isopoda	12.5				
Oribatidae	90.5	48.4	16.3	16.3	8.4
Mesostigmata-Uropodina	118.0	69.0	7.0	7.0	1.0
Trombidiformes	114.0	15.7	2.7	1.2	
Mesostigmata-Parasitidae	37.6	12.6	0.8		
Mesostigmata-Rhodocaridae	40.0	15.0			
Onychiuridae	42.4	14.2	11.4	6.8	1.1
Poduridae	20.8	7.7	5.2	2.4	1.1
Isotomidae	38.9	5.8	1.0	0.2	0.1
Sminthuridae	50.0	1.9			
Entomobryidae	31.2	2.6			
Diplopoda	30.4	26.1	26.1	4.3	
Symphyla	88.9	116.4	61.1	50.0	
Chilopoda	125.0	50.0	50.0		
Pauropoda	34.4	13.8			
Diplura	30.0				
Diptera	48.4	43.0	35.5	19.4	4.3
Coleoptera	55.5				

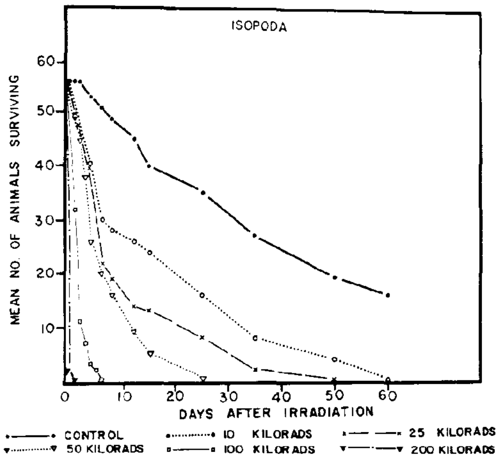

Fig. 5. Effects of different doses of gamma radiation on invertebrates in culture.

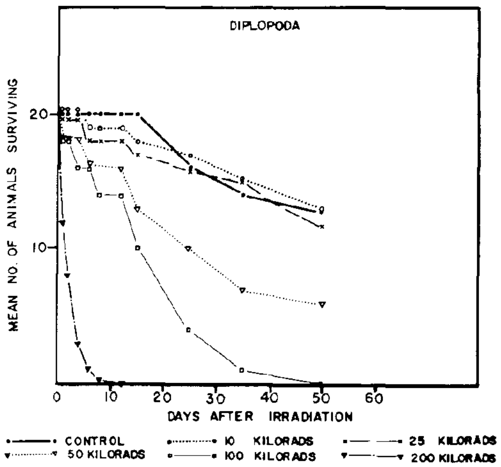

Fig. 6. Effects of different doses of gamma radiation on invertebrates in culture.

Table 2. Survival time in soil after treatment with 200 kilorads gamma radiation

Taxonomic Category	Minimum Time for 100% Mortality in Soil After Exposure to 200 Kilorads (days)
Isopoda	Less than 1
Chilopoda	
Collembola-Entomobryidae	10
Collembola-Sminthuridae	
Acarina-Parasitidae	20
Symphyla	
Pauropoda	
Diplopoda	
Thysanoptera	
Lumbricidae	
Enchytraeidae	30
Collembola-Isotomidae	40
Coleoptera adults	
Diptera larvae	
Nematoda	50
Collembola-Onychiuridae	70
Collembola-Poduridae	80
Acarina-Oribatidae	

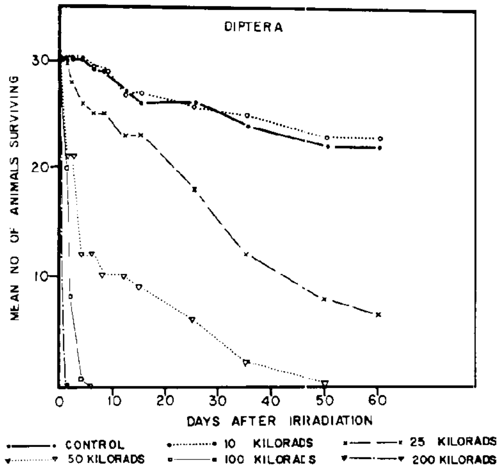

Fig. 7. Effects of different doses of gamma radiation on invertebrates in culture.

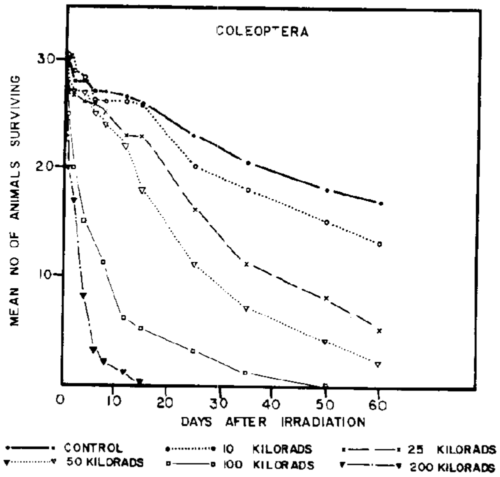

Fig. 8. Effects of different doses of gamma radiation on invertebrates in culture.

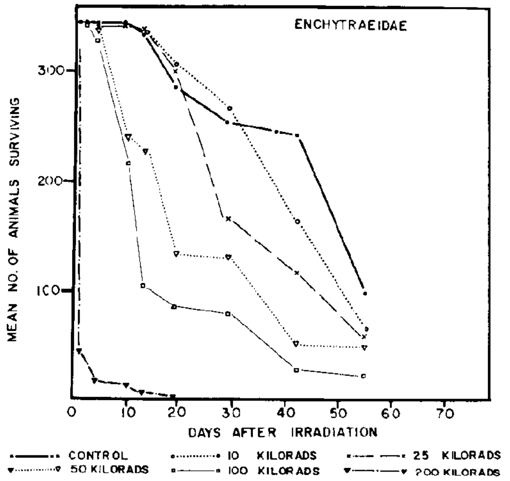

Fig. 9. Effects of different doses of gamma radiation on invertebrates in culture.

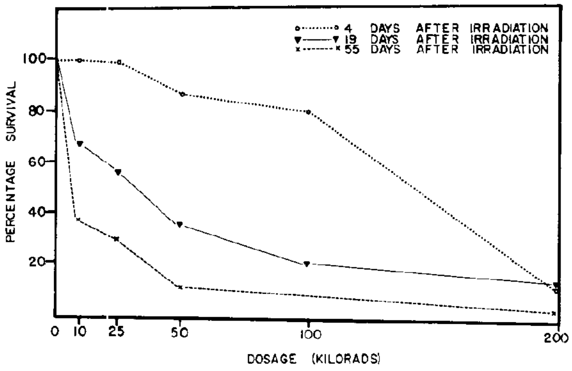

Fig. 10. Effects of dose rate on survival of all invertebrates in soil.

an underestimate. Hence, the figures quoted are the minimum times for 100% mortality. The relationship between survival time of the total population of invertebrates and radiation dose is summarized in Fig. 10.

Discussion

Most insects are killed by doses of gamma radiation in the range of one to fifty kilorads, although the eggs and immature stages may be susceptible to much lower doses. The investigations reported here show that other invertebrates have a similar range of susceptibility to radiation although some groups are more resistant. A dose of 200 kilorads was sufficient to kill all soil invertebrates in 80 days, and there was good evidence that a dose of 100 kilorads or less would ultimately eliminate most groups of invertebrates from soil. The susceptibilities of the common groups of small soil animals to a large dose of gamma radiation are compared in Table 2. The most striking feature of these data is the clear correlation between the activity and mobility of the animals and their susceptibility to the radiation. The more active animals, such as centipedes, wood lice, surface-dwelling Collembola (Entomobryidae and Sminthuridae), parasitic mites and symphylids were very much more susceptible to irradiation than the sluggish oribatid mites or deep soil-dwelling Collembola (Onychiuridae and Poduridae). Worms, nematodes, fly larvae and beetles are of intermediate activity and are also moderately susceptible to irradiation.

Irradiated soil invertebrates died sooner in plaster of Paris cultures than in intact soil samples stored at the same temperature. For example, although wood lice were killed in less than one day by 200 kilorads both in soil and in culture, millipedes survived for 8 days in culture and 20 days in soil after the same treatment. Enchytraeid worms survived for 19 days in culture and 40 days in soil, beetles for 15 days compared with 40 days in soil, onychiurid Collembola 50 days instead of 70 and oribatid mites 50 days instead of 80 days in soil. The most surprising results were, however, for the parasitic mites and dipterous larvae which were both killed in one day in the cultures by 200 kilorads, but in soil survived for 20 and 40 days respectively after treatment with the same dose. This may be that the species chosen to represent these two groups in the culture experiments were particularly susceptible to gamma radiation; certainly they were large and active species. The greater susceptibility of the culture animals is hardly surprising. They were living under unnatural conditions and in Table 2 only the time which the toughest individual of the most resistant species in the group required to die is recorded. Most species of invertebrates will be more susceptible to irradiation than this. The relative susceptibility of the various groups will be the same, however.

The pathological symptoms produced in the various groups of invertebrates by the radiation were varied and interesting. Animals from all groups showed a tendency to become much more sluggish and inactive after exposure to a large dose of radiation if it did not immediately kill or paralyze them. Individual responses to irradiation varied. In most groups, even when smaller doses were applied, some animals were dead immediately after treatment. At the other extreme, there were individuals that seemed resistant to very large doses. Paralysis was a common symptom and often lasted several days before death, with only periodic tremors of the legs and antennae to indicate life. This phase was most prolonged for the onychiurid Collembola, a few of these remaining paralyzed for two or three weeks before dying. None of the paralyzed animals ever recovered. Females of some species, in particular wood lice and millipedes, tended to lay eggs shortly before they died, but none of these were viable.

The relationship between dose and mortality was much more complex and variable than the relationship between insecticidal dose and mortality. This is not surprising because most insecticides have a single site of action, the stomach or nervous system, whereas gamma radiation is nonselective in its action; its effect varying only with the dose level and the susceptibilities of the different types of cell in the invertebrate body. Some invertebrates showed a steady increase in mortality as the radiation dose increased, e.g., oribatid mites (Fig. 4). By contrast, no uropod mites (Fig. 2) were killed until a threshold dose of 50 kilorads was applied; after this, a small increase in dose greatly increased mortality.

The mortality/time curves for the cultures at different dosages (Figs. 1–9) were very interesting. For most biocides mortality varies sigmoidally with time and approximates to a straight line when mortality is plotted on a probit scale and time is plotted on a logarithmic one. The gamma radiation data is plotted on linear scales in the figures, but when plotted on probit/log scales, there were two distinct phases; an initial stage complete for animals in all groups in six days or less, followed by a shallower secondary-mortality line that varied in slope for each group of animals and with the dosage of radiation applied. As the dose increased the number of animals killed in the first phase became greater. The mortality/time curves for *Tribolium confusum* (Cork 1967) clearly show two phases, but neither Cork nor other authors (Laviolette and Nardon 1963, Tilton *et al.* 1966) comment on this.

The corresponding data for the intact soil samples plotted as mortality/time curves also showed two distinct phases, and there were two phases to the mortality/dose curves when plotted on probit/log axes. There are several possible explanations for the form of these mortality curves; for example, possibly the animals in the cultures were heterogeneous in age or other factors were affecting their susceptibility to radiation. If this were so, it is unlikely that the two phases in the curves would be so consistent. A more probable theory is that there are two mechanisms of response to the radiation, the first producing a rapid or shock reaction which is complete in a few days. Those animals which escaped this damage would then succumb more slowly.

There is not space to give the full data for the effect of the doses of radiation on *populations* of different invertebrates in the soil samples, but Fig. 10 summarizes the effects of increasing dose rates on the survival of *all* the animals in the soil samples at a few representative time intervals. It clearly shows that treatment with 200 kilorads of gamma radiation greatly reduced the numbers of animals in soil even a few days after the irradiation. Seventy-six days after treatment with 200 kilorads, only three oribatid mites and one podurid Collembola remained alive compared with several thousand animals in the ten untreated control samples. It seems probable that the dose of radiation necessary to destroy all invertebrate animals and eggs in soil lies between 100 and 200 kilorads, but this may take several months. It could be much lower because although lower doses may not kill all the animals in soil, they may sterilize them and cause infertile mating so that the population eventually dies out. Single families or orders of invertebrates were completely eradicated by much lower doses as can be seen in Table 1. Such effects raise the question of the possible use of gamma irradiation as a technique for sterilizing soil for horticultural or other use. Although the packaging plant at Wantage could sterilize quantities of soil of the order of a few cubic yards, it would not be an economic proposition and the development of field methods of applying gamma radiation is even more difficult. It would involve the systematic dragging of a source and shielding, over land in order to obtain penetration to an effective depth, and as Cornwell and Bull (1960) observed, such operations could only be done by staff trained in handling of radiation sources and would be prohibitively expensive. As nuclear technology advances, however, such operations should not be excluded from the bounds of possibility.

The variation in susceptibility of different species of soil invertebrates to gamma irradiation may prove to be an invaluable tool in studying ecological interactions between various groups of animals in the terrestrial invertebrate community. It would be easy to choose a dose of radiation that would eradicate some groups of animals but leave others free to multiply reaching or increasing beyond their original numbers in a relatively short time. Rohde (1959) gave an example of differential susceptibility to radiation of a predator and its prey. He showed that the eggs of the parasitic mite *Fuscuropoda marginata* (C. L. Koch) were much more susceptible to gamma irradiation than those of its saprophagous prey *Caloglyphus mycophagus* (Megnin). If a dose of 50 kilorads is applied, probably the only animals living after several months would be oribatid mites, podurid and onychiurid Collembola.

The effects of the radiation on the populations of soil animals in the intact soil samples indicated the occurrence of this kind of interaction between predator and prey organisms. The parasitic mites were much more susceptible to the radiation than the isotomid, onychiurid and podurid Collembola and in the samples treated with 10 kilorads several species of isotomid and onychiurids increased considerably in numbers in the treated soil compared with the controls.

Although the animals in the samples have been sorted into families, the specific identifications are not yet complete; so, full details of the increases will be given in a future paper. Further investigations are being made into the effects of treatment with five kilorads to determine whether this dose will produce even more distinct increases in numbers of Collembola than the higher ones.

As Auerbach (1958) pointed out, we are still very ignorant of the soil ecosystem and on the long term effects of the contamination of this system with radioactive materials. It is certain that much more detailed study of both lethal and sub-lethal doses of radiation would be a fruitful field for ecological investigations and would greatly extend our knowledge of possible hazards and problems resulting from increases in the use of nuclear power and isotopes.

Acknowledgments

I wish to thank Mr. P. A. Cawse, Wantage Research Laboratory (AERE), Berks, England, for his advice and cooperation and for making radiation facilities available and Mr. A. E. Whiting of Rothamsted Experimental Station for considerable help with sorting the soil animals into taxonomic categories.

Appendix

Species of Animals Tested in Culture Experiments

Order	Family or Superfamily	Species
Collembola	Onychiuridae	*Onychiurus* sp.
Acarina	Uropodoidae	*Olodiscus minima*
	Parasitidae	*Alliphis halleri*
	Ceratozetoidae	*Punctioribates punctum*
Isopoda	Oniscoidae	*Porcellio scaber*
Diplopoda	Polydesmidae	*Polydesmus angustus*
Diptera	Stratiomyidae	*Pachygaster* sp.
Coleoptera		*Philonthus* sp.
Enchytraeidae		*Gen et sp.* unknown

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RADIOACTIVITY IN THE SEA

EFFECTS ON FISHERIES

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Effects on Fisheries

Most commercially important species of marine organisms are harvested in coastal waters where radiation from man's peaceful use of radioactive materials is most likely to reach highest levels. To date the greatest concentrations of radioactivity in aquatic environments have occurred in the open ocean in areas used as test sites for nuclear bombs. In addition to radiation from the relatively recent artificial radioactivity, marine organisms have been exposed to radiation from naturally occurring radioactivity for as long as life has existed in the oceans. Over the ages, organisms have been exposed to less radioactivity in the sea than on land because of the shielding capacity of water, and thus marine organisms possibly are more sensitive to it. In limited areas in the oceans, artificial radioactivity already has reached, on occasion, concentrations high enough to be deleterious to marine organisms, especially in the vicinity of radioactive waste disposal by sea burial.

The effects of radiation on marine organisms are very difficult to evaluate in the natural environment, e.g., near sites of nuclear bomb tests. Dead fish were observed after the detonation of nuclear devices at Bikini-Eniwetok, but it was believed that they died from blast effects (Ref. 5). Some fish in the immediate vicinity of the detonation of a large device, however, can be expected to receive lethal levels of radiation. If fish die as a result of radiation from radioactivity taken into their body or from radioactivity in the water, deaths would be expected over an extended period, as has occurred in laboratory experiments when organisms that were exposed simultaneously to one lethal level of radiation did not all die at the same time. It was also observed in the laboratory that greater differences in levels of radiation caused greater differences in time of death. The dose of radiation received by fish in the vicinity of a nuclear explosion would of course depend upon their distance from the explosion and the depth at which they were swimming. This gradient of radiation would be expected to extend the deaths over a long time and over a considerable area of the ocean. During the period between initial exposure to radiation and death, fish could migrate various distances. Although dead fish

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Rice, T. R. and J. W. Angelovic. 1969. Radioactivity in the sea: effects on fisheries. pp. 574-578. In: The Encyclopedia of Marine Resources. (F. E. Firth, ed.). Van Nostrand Reinhold, New York, New York.

have not been seen after a nuclear test (except near the bomb site), the possibility remains that most deaths have been unobserved, especially since fish weakened by radiation might be devoured by predators or succumb to other environmental stresses, seemingly unrelated to radioactivity in the ocean.

Although it is difficult to make in situ observations on the effects of radiation on organisms in the marine environment, at least one instance of adverse effects on marine organisms has been recorded; it resulted from the uptake of radioactive isotopes. This observation was made after the detonation of a nuclear bomb in the Marshall Islands. In 1958, Gorbman and James (Ref. 10) found evidence that herbivorous fish concentrated radioactive iodine from seaweeds that had previously accumulated this radioisotope from seawater. Carnivorous fish then further concentrated the iodine to such high levels that their thyroid glands were destroyed. Although radioactive iodine is accumulated by marine organisms, it is usually not of serious concern except in areas receiving close-in fallout. Since the radioactive decay rate of iodine 131 is relatively rapid (half-life, 8 days), and since iodine 131 is diluted with stable iodine in seawater, marine organisms seldom accumulate enough of it to result in detectable injury.

Beneficial changes in marine organisms from exposure to radiation also are difficult to detect and evaluate in the natural environment. For instance, to detect an increase in growth rate, physiological vigor, or survival for organisms in the sea usually requires observations over a considerable period of time. Even though this time-consuming evaluation is usually required, Blinks (Ref. 1) has reported an effect of radiation on plant species that might be construed as beneficial. Marine algae in the most radioactive area on the Bikini Island reefs, one year after a nuclear bomb blast, had greater catalase activity than algae from a nonradioactive area. Blinks tentatively explained this phenomenon as an enzyme adaptation that protected the organism from the hydrogen peroxide produced by radiation.

Even though few observations have been made of the effects of radiation on animals and plants in the marine environment, additional knowledge has been gained from experiments conducted in the laboratory. Before considering data obtained from laboratory experiments, however, the origin of radioactivity in the marine environment, the characteristics of radiation, and the sensitivity of living material to radiation will first be explored.

Ionizing Radiation. Marine organisms are now subjected to radiation originating from radionuclides that occur naturally and from those that are artificially produced. Natural radionuclides have existed since the earth was formed and have found their way to the oceans, in part at least, from the weathering of rock. The principal categories of natural radionuclides are: (1) primordial radionuclides and their decay products (daughters); and (2) radionuclides resulting from reactions between cosmic rays and elements in the atmosphere or in the earth. More than a dozen long-lived naturally occurring radionuclides have been identified. Most of the natural radiation in the seas originates from only three of these radionuclides: potassium 40 (which alone accounts for more than 90% of the natural radiation); uranium 238, and thorium 232. Artificial or man-made radionuclides have been added to the sea in measurable amounts since 1945, primarily through the explosion of nuclear weapons and through planned or accidental discharges from nuclear installations. Whereas natural radionuclides are more or less evenly distributed throughout the oceans, concentrations of artificially produced radionuclides vary with time and location.

Radioactive substances emit one or more of the three different kinds of radiation: alpha particles, beta particles, and gamma rays. The rate at which a radioactive isotope disintegrates or decays is completely independent of external conditions. Thus, a constant proportion of the radioactive atoms present will disintegrate in a given period of time independently of the total number present. Approximately 30 different natural radioisotopes emit alpha particles and about the same number emit beta particles, whereas only about half this number emit gamma rays. Ionizing radiation is capable of penetrating matter, it possesses great energy, and most types are electrically charged. This radiation is referred to as "ionizing radiation" because of its capacity to eject planetary electrons from atoms—resulting in ions.

Response of Organisms to Radiation. A quantitative relation exists between the extent of damage to an organism and the amount of radiation it receives. Dose can be plotted against effect in two ways (Fig. 4), but opinions differ as to which curve shows the correct relation. The usual biological response to most physical and chemical factors is shown by the dotted line of Fig. 4. As can be seen, there is no effect until a certain dose is received. This is called a "threshold response." Theoretically, any dose less than threshold will cause no effect. The "non-threshold" relation between dose and effect is illustrated by the solid line, which runs through the origin. Since the relation is linear, any dose, however small, will have a measurable effect directly proportional to the size of the dose. It is assumed now that genetic effects of radiation follow this type of dose-effect curve.

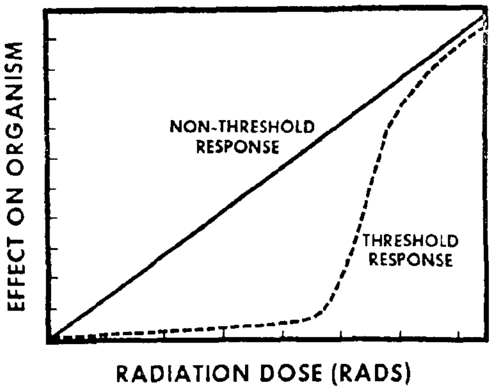

Fig. 4. Two concepts of the response of organisms to radiation. (After Comar.)

Damage from radiation takes place at the most fundamental level—in the cells of organisms. The process by which this damage occurs, however, remains more or less a mystery. Radiation affects cells in many ways: it may kill them, change their rate of growth and division, and alter their genes and chromosomes so that their progeny inherit different characteristics. Cells that are dividing rapidly are more sensitive to radiation than less active ones. Since the well-being of a cell depends on its metabolism, it is here that investigators have looked for the basic effects of radiation. The effects result from the ionizing action of radiation on atoms and molecules within the cell. Ionization involves the removal of an electron from a neutral atom, creating a positive ion. This released electron reacts with another atom to form a negative ion. Thus ion pairs result from ionization. It is believed that ionization is the major cause of injury to protoplasm and that the damage is proportional to the number of ion parts produced. Radiation ionizes atoms in its path impartially, whether contained in water, proteins, enzymes, hormones, or other biologically important substances. This change in structure of biochemically important molecules disrupts the structural components of the cell and reduces the cell's metabolic efficiency.

A comparison of data on the effects of radiation on organisms indicates that phyla differ in their response (Fig. 5). The more primitive organisms are usually more resistant than the more complex animals, such as fish. Variation between related species is considerable, however. For example, 50% of the snails, *Radix*, exposed to 10,000 roentgens (R) died after about 1 month, whereas another group of snails, *Thais*, exposed to the same dose lived for about 6 months (Ref. 2). Price (Ref. 15), who irradiated two species of shellfish, found that about 93,000 R killed 50% of the oysters, *Crassostrea virginica*, in 34 days and 50% of the clams, *Mercenaria mercenaria*, in 38.5 days. This similarity in survival time would appear to indicate a similar response to radiation for the two species. If LD-50's (the amount of radiation needed to kill 50% of the organisms) are calculated earlier or later than 30 days after irradiation, however, the tolerances of the two species are not similar (Ref. 19). Oysters have an LD-50 almost twice that of clams 20 days after irradiation and only one-fourth that of clams 40 days after irradiation.

Different stages in the life cycle of a species also differ in sensitivity to radiation (Table 5).

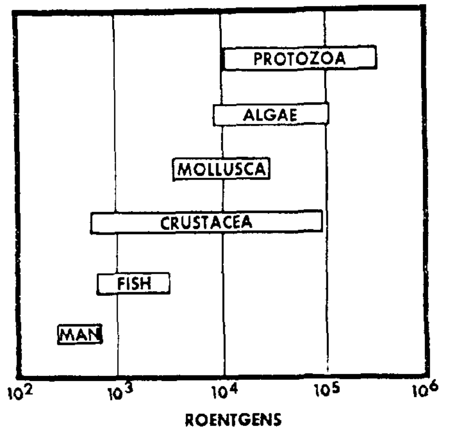

Fig. 5. Dose of X rays or gamma rays required to kill 50% of organisms. (After Donaldson.)

TABLE 5. AMOUNTS OF RADIATION REQUIRED TO KILL 50% OF THE RAINBOW TROUT, *Salmo gairdneri*, IRRADIATED AT VARIOUS STAGES IN THEIR LIFE CYCLE[a]

Stage in Life Cycle	LD-50 (R)
Gametes	50–100
1 cell	58
32 cell	313
Germ ring	454–461
Eye	415–904
Adult	1,500

[a] After Welander (Refs. 16, 18).

Gametes and eggs through the one-cell stage are very sensitive to radiation, for example, during mitosis of the single cell of silver salmon, *Oncorhynchus kisutch* the LD-50 is only 16 R (Ref. 6). The sensitivity of rainbow trout (*Salmo gairdneri*) decreases with increasing age (Refs.

16, 18), and this relation appears to be the general rule for other species.

Since sensitivity to radiation is correlated with the metabolic rate of the cell, it is not surprising that the dormant eggs of aquatic invertebrates are especially resistant. The eggs of the brine shrimp, *Artemia salina*, that have been placed in water so that embryonic development is resumed are more than twice as sensitive to radiation as the dry dormant eggs (Ref. 2). Results of experiments on the effects of radiation (strontium 90-yttrium 90), on the eggs of the plaice have been inconsistent: Fedorov et al. (Ref. 7) reported very high sensitivity to low concentrations, whereas Brown and Templeton (Ref. 3) found no effect at concentrations as high as 10^{-4} c/l (curies per liter). Polikarpov and Ivanov (Ref. 14) found that a concentration of 10^{-10} c/l of strontium 90-yttrium 90 was sufficient to cause a significant number of abnormal larvae in five species of marine fish. Concentrations of radioactivity in the sea have sometimes reached or exceeded this level. Strontium 90 has been reported at concentrations of 10^{-12} and 10^{-11} c/l in the Pacific Ocean and Irish Sea (Refs. 12, 11); in 1959 the waters of the Irish Sea contained as much as 10^{-11} c/l cesium 137, 10^{-10} c/l cerium 144, 10^{-10} c/l zirconium 95, and 10^{-9} c/l ruthenium 106 (Ref. 11).

The rates of increase in both length and weight of fish can be slowed by radiation. Irradiation of rainbow trout eggs retarded the development of the young and increased the number of abnormalities (Ref. 16). Somatic damage was proportional to the amount of radiation received, and the greatest amount of damage was in tissues that were growing and dividing rapidly (Ref. 17). Also, the growth of young rainbow trout from irradiated parent stock was considerably slower than that of the young from unirradiated parents (Ref. 9).

Influence of Radiation on Populations. Populations of fishery organisms exposed to radiation may be adversely affected. If the deleterious effects of the radiation occur simultaneously with other unsatisfactory conditions, such as a shortage of food, excessive predation, or disease, the population naturally will suffer a greater reduction than it would if the radiation exposure occurred during a period of optimum conditions. Certain combinations of these deleterious factors may be sufficient to reduce the population to extinction or to the point of no recovery. Two primary considerations for evaluating effects of radiation on populations are: (1) the cumulative dose of radiation, and (2) the tolerance of the most sensitive stage. If exposure is continuous, the life span of organisms becomes critical in considering levels of radiation and their effects, because the cumulative dose received by an organism is equal to the level of radiation multiplied by length of exposure. The time of exposure of a population to acute doses of radiation is also important. For instance, if exposure to radiation occurs during spawning, the most sensitive stage in the life cycle, i.e., the egg, would be irradiated.

Fish eggs are very sensitive to radiation and may be more important in relation to radiation effects on populations than is presently believed by many investigators. For instance, the assumption has been made that when 50% or more of a population is lost, the commercial fishery for the species in the region concerned may cease to exist. The time required to lose half a fishery when different percentages of eggs are damaged, as calculated by Zaystev and Polikarpov (Ref. 20), is shown in Table 6. If radiation affects more than 10% of the eggs, commercial catches of fish will decrease appreciably. These calculations, however, were based on the assumption that the percentage of eggs damaged each year would remain constant. There is no way to predict the effect at any given time because the amount of radioactivity in the water and other factors which influence the size of the population fluctuate irregularly. High levels of radioactivity in conjunction with low spawning success could result in a large reduction.

TABLE 6. TIME REQUIRED TO REDUCE POPULATIONS OF FISH 50%, ON THE BASIS OF THE PERCENTAGE OF EGGS DESTROYED[a]

Eggs Destroyed, %	Time (years)		
	Mullet	Horse-mackerel	Anchovy
5	55	68	100
10	29	34	50
20	15	18	25
30	11	13	17
40	8	10	13
50	7	8	10

[a] After Zaystev and Polikarpov (Ref. 20).

Radiation can affect not only a population of fishery organisms receiving the radiation but also the descendants of the population. Somatic changes to the individuals of a population, if they are severe enough and if they occur in sufficient numbers, can reduce the population immediately. Establishing the occurrence of a genetic change in a population is more difficult than detecting somatic damage. Most mutations are not advantageous to the animal and are eliminated because the animals with the mutations cannot compete with the existing population. For instance, if the genetic change results in slower movement, the affected animals would probably be the first to fall prey to predators, and the chances of the mutations becoming established in the population would be reduced. The probability of a mutation becoming established in a breeding population is highest in populations isolated from other similar breeding populations. Possibly populations of sedentary organisms (i.e., animals that only move over short distances), or highly motile animals with restricted breeding groups (such as the salmon, which spawns in the same stream in which it was reared), would be types of population in which new mutations would have a better chance of becoming established.

In addition, radiation damage can affect individual organisms—and thus populations—by reducing the rate of growth, shortening the life span, reducing fecundity, and changing behavior. How radiation affects marine organisms in these ways is not well understood. There is little doubt, however, that levels of radioactivity in the seas, particularly in coastal waters, will continue to increase as man increases the use of nuclear energy. That the maximum levels of radionuclides now allowed in natural waters may occasionally result in damage to aquatic organisms already has been demonstrated (Ref. 8). Also, catastrophic or emergency conditions may occur at any time and would definitely result in damage to marine organisms. For these reasons it is necessary that more research be carried out on the effects of radiation on marine organisms.

T. R. Rice
J. W. Angelovic

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CHROMOSOMAL POLYMORPHISM IN IRRADIATED NATURAL POPULATIONS OF CHIRONOMUS[1]

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CHROMOSOMAL polymorphism occurs in many species of Drosophila and Chironomus. Evidence has been accumulated by BEARDMORE, DOBZHANSKY and PAVLOVSKY (1960), BATTAGLIA and SMITH (1962), and others that chromosomal polymorphic populations are superior in fitness to monomorphic populations. In most cases it is accepted that populations remain chromosomally polymorphic because the heterokaryotypes are superior in fitness to the homokaryotypes. The viabilities of the different chromosomal forms may be so delicately adjusted to the environment that subtle changes can have a marked effect on their frequencies.

It is well known that the exposure of living organisms to ionizing radiation may result in genetic damage in the form of gene mutation and chromosome aberrations. However, the effect that ionizing radiation would have on balanced chromosomal polymorphism in natural populations is not clearly understood. SEECOF (in STONE *et al.* 1957) detected no increase of new chromosome rearrangements in heavily irradiated natural populations of *Drosophila ananassae*. CORDEIRO (1961) found two new inversions and a marked decrease in chromosomal polymorphism in isolated natural populations of *D. willistoni* that had received large releases of progeny from heavily irradiated parents. PAGET (1954) observed some new inversions at high frequencies in WALLACE and KING's (1951) chronically irradiated laboratory populations of *D. melanogaster*. MOURAD (1962) utilized the phenomenon of balanced chromosomal polymorphism in caged populations of *D. pseudoobscura* to show that irradiated chromosomes decline in frequency for a generation or two, but recover and establish a balanced equilibrium at a frequency below the controls. In MOURAD's populations, when irradiated chromosomes were added to each generation, an equilibrium strikingly below the controls was reached.

BLAYLOCK (1965) found several chromosomal aberrations unique to a population of Chironomus living in a stream contaminated by radioactive waste. Three paracentric inversions occurred at a relatively high frequency in this irradiated natural population. This report concerns a comparison of the chromosomal polymorphism produced by these three inversions in the irradiated population with a nonirradiated population. In addition, the finding of more unique aberrations in

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Blaylock, B. G. 1966. Chromosomal polymorphism in irradiated natural populations of Chironomus. Genetics 53(1):131-136.

the irradiated population is reported and chromosomal polymorphism in the irradiated population is discussed.

MATERIALS AND METHODS

The species studied belongs to the plumosus group and was referred to as *Chironomus tentans*; the natural populations sampled in this study were described in detail by BLAYLOCK (1965). The irradiated population is located near Oak Ridge, Tennessee in White Oak Creek, an area that has been contaminated with radioactive waste from the Oak Ridge National Laboratory since 1943. The calculated dose the larvae are receiving, based on radionuclide content in the bottom sediment, is approximately 230 rads per year (NELSON and BLAYLOCK 1963). The largest nonirradiated population is located at Ten-Mile Creek about 16 miles from White Oak Creek. The majority of the larvae were collected from July to January. Usually collections of the fourth-instar larvae were made from the irradiated and nonirradiated populations during the same week. Temporary aceto-orcein and carmine salivary squashes were made from the larvae shortly after collection.

RESULTS

The number of different chromosome aberrations observed in irradiated and nonirradiated populations is given in Table 1. This table includes the data on chromosome aberrations given by BLAYLOCK (1965) plus aberrations observed in additional collections. Two new paracentric inversions involving several bands were observed only one time in 327 additional larvae from the irradiated population. Column one shows a total of 17 different aberrations which were observed in the irradiated population. The second column shows that only six different inversions were observed in the nonirradiated populations and that all six of these inversions were also found in the irradiated population. These inversions were found in each population more than one time and three—inversions 1Ra, 2Lab and 3Ra—occurred at a relatively high frequency. Eleven aberrations—ten inversions and one deletion—were found only in the irradiated population. All of these 11 aberrations were observed once except one inversion, which was found five times in two collections from one site and is probably the result of one event (BLAYLOCK 1965).

In Table 1 under nonirradiated populations the total number of larvae analyzed is composed of 407 from Ten-Mile Creek, 248 from McCoy Branch and 59 from the Clinch River. In the remaining tables, only the collections from Ten-Mile Creek were compared with the irradiated population from White Oak Creek.

TABLE 1

Chromosome aberrations in irradiated and nonirradiated natural populations of Chironomus tentans

	Irradiated population	Nonirradiated populations
Larvae analyzed	692	714
No. of different inversions found in both populations	6	6
No. of different inversions unique to one population	10	0
No. of deletions unique to one population	1	0

These data include the White Oak Creek (irradiated), the Ten-Mile Creek (nonirradiated), as well as other populations.

The data shown in Table 2 indicate that the endemic inversions, 1Ra, 2Lab and 3Ra, are well established in the irradiated population and that their frequencies do not change from year to year. An appropriate chi-square analysis of the frequencies of the inversion heterozygotes collected in July and August of 1961 to 1964 showed no significant changes at the 5% level of statistical significance.

The data in Table 3 are an index to the degree of chromosomal polymorphism in the irradiated and nonirradiated populations. These data show that all possible combinations of the inversion heterozygote are viable and are found in both the irradiated and nonirradiated populations. The other three endemic inversions occurred at a very low frequency in both populations and are not shown in this table.

Table 4 is a comparison of the frequencies of the inversion heterozygotes of 1Ra, 2Lab, and 3Ra in the irradiated and nonirradiated populations. Since no seasonal fluctuation of these inversions was detected in either White Oak Creek or Ten-Mile Creek (BLAYLOCK 1965), the total collection from 1962–64 from White Oak Creek was compared with the total collections from Ten-Mile Creek. A chi-square analysis showed no detectable difference in the frequencies of the inversion heterozygotes in the irradiated and nonirradiated populations.

The inversion homozygote of 1Ra was observed, but the homozygotes of inversions 2Lab and 3Ra were not detected. When the binomial square test was

TABLE 2

Five year comparison of three endemic inversion heterozygotes found in the White Oak Creek population

	1960 July	1961 July-Aug.	1962 July-Aug.	1963 July-Aug.	1964 July-Aug.	χ^2	P (4 df)
No. larvae analyzed	31	56	45	97	79	...	......
Inversion 1Ra	8	9	5	12	13	4.09	.50–.25
Inversion 2Lab	7	7	6	23	9	6.63	.25–.10
Inversion 3Ra	3	5	4	6	3	2.31	.75–.50

TABLE 3

Inversion heterozygosity in larvae of the irradiated and nonirradiated populations

Inversion(s) heterozygous	Irradiated (White Oak Creek)	Nonirradiated (Ten-Mile Creek)
1Ra	53	46
2Lab	73	58
3Ra	21	34
1Ra and 2Lab	12	21
1Ra and 3Ra	1	2
2Lab and 3Ra	13	6
1Ra, 2Lab and 3Ra	1	5
No inversion heterozygous	265	245

TABLE 4

Frequency of inversion heterozygotes in irradiated and nonirradiated natural populations

	Irradiated (White Oak Creek) 1962–64	Nonirradiated (Ten-Mile Creek) 1962–64	χ^2	P (1 df)
No. of larvae analyzed	439	407	...	......
Inversion 1Ra	67	74	1.29	.50–.25
Inversion 2Lab	99	90	0.02	.90
Inversion 3Ra	36	37	0.22	.75–.50

applied to inversion 1Ra from the irradiated and nonirradiated populations, the equilibrium condition was satisfied in both populations and the conformity to the expected frequencies shown in Table 5 is exceedingly good.

DISCUSSION

The finding of two new inversions in additional sampling from the White Oak Creek population further confirms the previous conclusion by BLAYLOCK (1965) that genetic damage is being produced in the Chironomidae population by chronic low-level environmental radiation. The finding of new aberrations in the irradiated population agrees with PAGET's (1954) observations of new aberrations in laboratory populations of *D. melanogaster* and with CORDEIRO's (1961) findings in natural populations of *D. willistoni*. However, the organisms and irradiation exposures in each case were quite different. In the Chironomus population the larvae are not only living in the radioactive bottom sediments of the stream, but they are also ingesting radionuclides with their food. In the laboratory populations studied by PAGET, the populations had received approximately 5r per hour for about 100 generations while the isolated populations of *D. willistoni* received large releases of progeny from heavily irradiated flies (5 to 10kr) every month. CORDEIRO (1961) not only found two new inversions in the natural population of *D. willistoni*, but he also found a decrease in chromosomal polymorphism.

TABLE 5

Analysis of inversion 1Ra in the irradiated and nonirradiated population by the Hardy-Weinberg Law

Location		Structure types s/s	s/i	i/i	χ^2	P (1 df)
Irradiated						
(White Oak Creek)	Obs.	367	67	5		
	Exp.	364.4	70.2	4.4	.25	.75–.50
Nonirradiated						
(Ten-Mile Creek)	Obs.	330	74	3		
	Exp.	329.7	73.3	4.0	.25	.75–.50

s = standard sequence. i = inversion sequence.

BEARDMORE, DOBZHANSKY and PAVLOVSKY (1960) and BATTAGLIA and SMITH (1962) have shown that in experimental population cages of *D. pseudoobscura* polymorphic populations produced more individuals and a greater biomass than monomorphic populations on the same amount of food. DOBZHANSKY and PAVLOVSKY (1961) and STRICKBERGER (1963) using different techniques arrived at the same conclusion that polymorphic populations are superior in fitness to monomorphic populations. Recently, DOBZHANSKY, LEWONTIN and PAVLOVSKY (1964) found that polymorphic populations were superior in their innate capacity for increase. If we accept polymorphic populations as being superior to monomorphic populations, then a decrease in chromosomal polymorphism could indicate a decrease in fitness of the population.

MOURAD (1962) has shown that in laboratory populations of *D. pseudoobscura* irradiated chromosomes reach an equilibrium below the equilibrium established in control populations. CORDEIRO (1961) suggested that lethals trapped in the inverted segments of the chromosomes were responsible for the decrease in the chromosomal polymorphism in the natural populations of *D. willistoni.*

The Chironomus population at White Oak Creek gives some information on chromosomal polymorphism in a natural population exposed to chronic radiation. There is little doubt that this population has suffered genetic damage from the high radiation background. However, the five-year comparison of the frequencies of the three endemic inversions (Table 2) shows that these inversions are well established at certain frequencies in the irradiated population. The comparison of the inversion frequencies in White Oak Creek with the inversion frequencies in Ten-Mile Creek (Table 4) shows that the degree of chromosomal polymorphism produced by these inversions is not significantly different in the irradiated and nonirradiated populations. Or if there was an initial effect produced on the frequencies of these inversions by ionizing radiation, the population had compensated for it. The exceedingly close fit of inversion 1Ra (Table 5) to the expected Hardy-Weinberg frequencies in both the irradiated and nonirradiated populations indicates that in no way is the exposure to chronic radiation affecting the equilibrium of this inversion. Thus, we can conclude that the chronic environmental radiation which is capable of producing a detectable increase of new chromosomal aberrations is not affecting the frequencies of the endemic inversions in the White Oak Creek population.

SUMMARY

Chromosomal polymorphism in a natural population of *Chironomus tentans* inhabiting a stream contaminated by radioactive waste was compared with a nonirradiated population. Ten inversions and one deletion were found in the irradiated population but not in the control population. The frequencies of three endemic inversions which were found in both populations were not significantly different in the irradiated and nonirradiated populations. It was concluded that in the irradiated population, where an increased frequency of new chromosome aberrations was detected, the frequencies of the endemic inversions were unchanged by the chronic radiation.

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THE EFFECTS OF CONTINUOUS, SUB-LETHAL GAMMA RADIATION ON THE INTRINSIC RATE OF NATURAL INCREASE AND OTHER POPULATION ATTRIBUTES OF *Daphnia pulex*[1]

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The intrinsic rate of natural increase and concepts associated with it are among the most fundamental of ecological principles. In view of this, and considering how little is known of the population consequences of radiation, I undertook to determine how a species' intrinsic rate of natural increase might be affected by continuous, sub-lethal intensities of gamma radiation.

Daphnia pulex was chosen for this study because of its convenient size, short life-span, and the relative ease with which a large number of experimental animals can be cultured under reproducible conditions.

The intrinsic rate of natural increase and other population attributes to be discussed were calculated from 21 tables of age-specific survivorship and fertility in cohorts of *Daphnia* exposed to different intensities of gamma radiation almost continuously throughout post-natal life. The present experiment was initiated with 50 newborn daphnids at each of the 21 different radiation levels.

Figure 1 shows the effect of continuous gamma radiation on the intrinsic rate of natural increase. The vertical axis indicates the instantaneous rate of increase per head of population. The horizontal axis shows the dose rate to which the daphnids were exposed. The dashed line indicates where the intrinsic rate equals zero. Each point represents a single population.

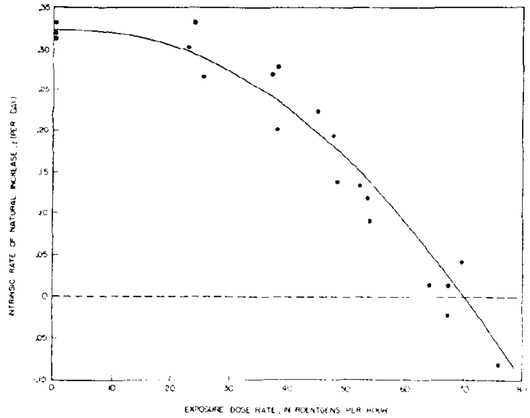

Figure 1. The effects of continuous gamma radiation on the intrinsic rate of natural increase *Daphnia pulex*. Line fitted by eye.

It is highly unlikely that these points and the line drawn through them represent the absolute maximum intrinsic rate of natural increase at all radiation intensities. They would do so only if all the other environmental conditions (except those produced directly or indirectly by the radiation) were an optimal combination at all radiation intensities. However, to the extent that they were optimal, what do these results signify? What predictions could be made?

First of all, the radiation intensity at which the maximum intrinsic rate of natural increase equals zero would just enable a population whose density was optimal to maintain an equilibrium if the environment remained constantly optimal (except for the radiation). In nature, therefore, where the favorability of the environment is certain to fluctuate at least slightly, a population with a maximum intrinsic rate of zero will be eliminated. For continuous radiation, then, these results cover the complete range of intensity of ecological interest, since beyond 70 roentgens per hour *Daphnia pulex* populations could not exist—at least not for long. Populations with maximum intrinsic rates below zero would rapidly disappear even if the environment (except for radiation) remained constantly optimal.

Now let us consider the lower range of radiation intensities near zero, or background levels. It is entirely possible that there is some "threshold" radiation intensity, below which there is no reduction of intrinsic rate, although these results don't show it. Let us just assume for the moment that any permanent increase of radiation in the environment will produce at least a temporary decrease in the maximum intrinsic rate of the species exposed. How would a species, so exposed, be affected in nature?

If a single species experiences a reduction in its maximum intrinsic rate of increase, it will theoretically suffer at least some decrease in average abundance. This is assuming the simplest case where no other species are affected. If other species in a community are also being exposed to an increased radiation intensity, the consequences for a single species population cannot be predicted from knowledge limited to the population level for that species alone. Nevertheless, the present type of information can be used to predict what intensities of radiation would certainly cause complete extinction of a population.

I would therefore like to define an index of comparative radiation sensitivity——for comparing species in radioecological work. To my knowledge we do not at present have an index that has any meaning at the population level of integration. Therefore, I propose using that intensity of continuous radiation at which a species' maximum intrinsic rate of natural increase equals zero as an index of species radiosensitivity.

The intrinsic rate of natural increase is the end-product of many underlying processes. The processes immediately underlying it are the population birth rate and death rate.

Figure 2 shows the effects of continuous gamma radiation on the population birth rate and death rate. The numerical values of both are indicated on the vertical axis. The circles represent death rates; the dots, birth rates.

Since the intrinsic rate of natural increase is the difference between the birth rate and death rate, it is clear from this figure that the reduction of the intrinsic rate of *Daphnia* is mainly caused by a drop in the birth rate. The death rate

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[1] The definitive paper on which this report is based has been accepted for publication in *Ecology*.

Marshall, J. S. 1963. The effects of continuous, sub-lethal gamma radiation on the intrinsic rate of natural increase and other population attributes of *Daphnia pulex*. pp. 363-366. In: *Radioecology*. (V. Schultz and A. W. Klement, Jr., eds.). Reinhold, New York, New York.

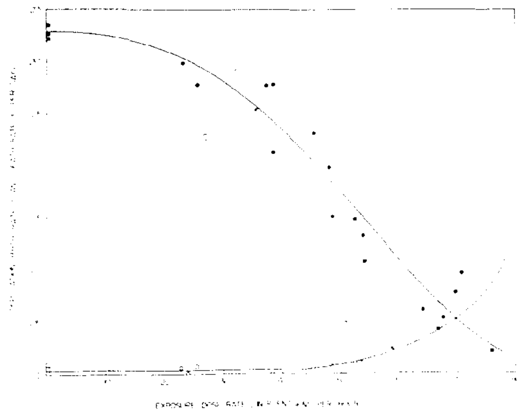

Figure 2. The effects of continuous gamma radiation on the population birth rate (dots) and the population death rate (circles) of Daphnia pulex. Lines fitted by eye.

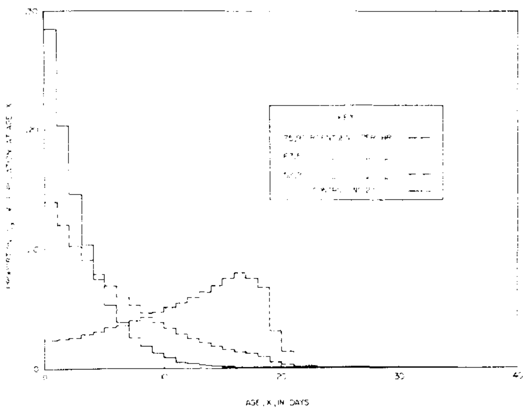

Figure 3. The effects of continuous gamma radiation on the stable age distribution of Daphnia pulex. Out of the 21 populations, only four representative ones are illustrated. The dose rate to which each was exposed is indicated by the key.

is not significantly affected below 45 roentgens per hour, although the birth rate becomes cut in half in this range.

The reason for this is because individual mortality rates were not significantly affected until late in reproductive life, while individual fertility rates showed a high degree of inverse correlation with dose rate from the very beginning of reproduction.

The death rate begins to rise abruptly beyond 50 roentgens per hour and becomes equal to the birth rate at about 70 roentgens per hour. At this point the difference between them—the intrinsic rate of natural increase—equals zero.

The birth rate rapidly approaches zero above 70 roentgens per hour. From a pilot experiment I found that the birth rate reaches zero somewhere below 140 roentgens per hour.

The birth rate and death rate are each determined by the underlying pattern of age-specific fertility or survivorship of individuals throughout life and the proportion of the population made up by individuals of each age class--the age-distribution. Consequently, a change in either the age-distribution or mortality rates alone would affect the population death rate. For instance, in the present case, mortality rates were increased and life-span was shortened, but these effects had little influence on the results at the population level. The rising death rate beyond 50 roentgens per hour is due almost entirely to an increasing proportion of older individuals in these populations. Most of this increase in the death rate in this range would have occurred even if mortality rates—hence survivorship—had not been affected at all. The effects of radiation on individual mortality rates or life-span, by themselves, have no definite meaning at the population level. A population's age-distribution is at least equally as important as individual life-history.

Figure 3 shows the effect of continuous gamma radiation on the age-distribution. Only four of the 21 populations are represented, but these four suffice to illustrate the effect of increasing radiation intensity. The vertical axis indicates the proportion of the population made up by individuals of a given age class. The age classes are indicated by the horizontal axis. Each age class spans an interval of one day. The total area under each age-frequency histogram equals unity.

The control population has a relatively large proportion of newborn animals (zero to one day old), and the proportion of individuals in older age classes decreases rapidly with age. The proportion of individuals older than ten days is negligible in comparison with the proportion of younger individuals, and an individual as old as 35 days is extremely rare.

The effects of increasing radiation intensity are mainly a decrease in the proportion of immature individuals (less than five days old) and an increase in the proportion of middle-aged adults. The proportion of young adults is relatively unaffected. In non-steady-state populations, therefore, the proportion of older individuals can be increased, even though life-span is decreased, by increasing intensities of radiation.

In the population receiving 67.5 roentgens per hour (indicated by dots), the intrinsic rate of natural increase is still positive but very close to zero. For this reason, this age-distribution is almost solely determined by the survival curve for individuals in the population.

The population receiving 75.9 roentgens per hour has a negative intrinsic rate of natural increase. As one would expect, a rapidly declining population is composed of a relatively large number of older individuals and few in the youngest age groups.

Figure 4 shows how life-span was decreased by increasing radiation. These are the survival curves for individuals in seven of the 21 populations. The vertical axis indicates the proportion of a group of newborn daphnids remaining alive at a given age. The horizontal axis indicates the age in days.

The individual survival curves in all 21 populations approached the ideal, "rectangular" type. The effect of increasing dose rate was mainly a progressive shift to the left.

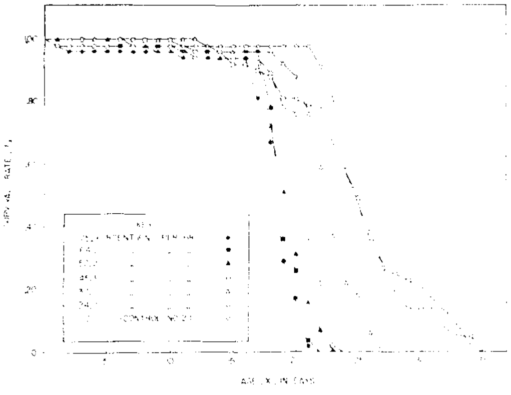

Figure 4. Seven representative survival curves for Daphnia pulex exposed to different dose rates (indicated by key) of continuous gamma radiation.

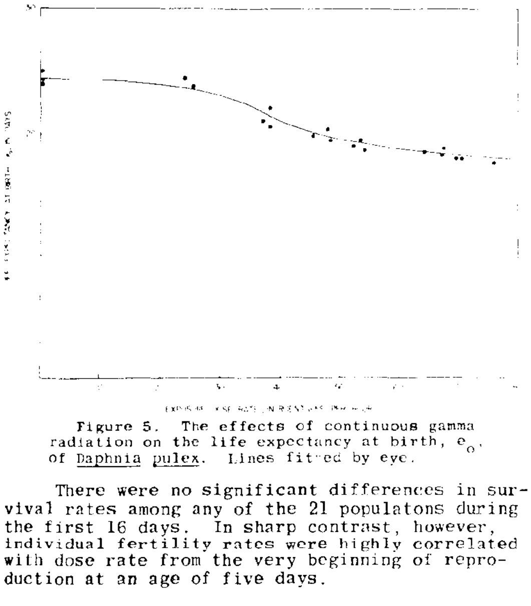

Figure 5. The effects of continuous gamma radiation on the life expectancy at birth, e_o, of Daphnia pulex. Lines fitted by eye.

There were no significant differences in survival rates among any of the 21 populatons during the first 16 days. In sharp contrast, however, individual fertility rates were highly correlated with dose rate from the very beginning of reproduction at an age of five days.

Figure 5 shows the effect of continuous gamma radiation on individual life-expectancy at birth. In populations with a stable age distribution this statistic is the same as average life-span. The effects of radiation on life-span or other individual attributes were not the main concern of the present study. The main point I wish to make with this figure is that, for Daphnia pulex, these are sub-lethal intensities of radiation. Neither the shape of the survival curve nor average life-span was drastically altered.

Individual fertility rates, to repeat, were drastically altered, and this effect was statistically significant long before significant differences in survival rates developed. The reduction of fertility rates with increasing dose rate was due almost entirely to decreasing egg production rather than increasing pre-natal mortality.

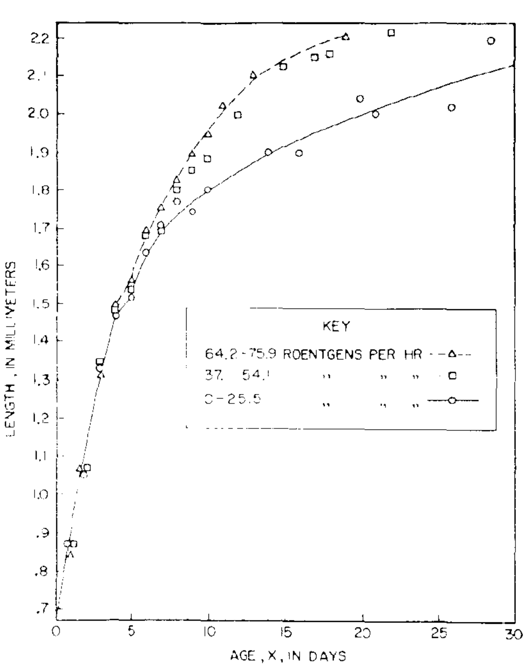

Figure 6. Individual growth in length of Daphnia pulex exposed to "high" (triangles), "medium" (squares), and "low" (circles) intensity ranges of continuous gamma radiation. Each point represents average length of six or more measured individuals. Lines fitted by eye.

The effects observed on survival or life-span are taken as a measure of the effects of the radiation on the individuals' somatic tissues and physiological condition. The fact that fecundity disclosed drastic effects from the very beginning of adulthood while survival rates were not affected until late in life led me, in part, to conclude that the reduction of fecundity was due to direct effects of the radiation on the cells of the ovaries and not to indirect, physiological effects.

Figure 6 shows the effects of the radiation on individual growth in length. Individual growth increased with increasing dose rate. This may seem surprising at first. However, in Daphnia, the eggs are rather large in relation to the animal that produces them. It is most likely that the increased growth at higher dose rates is simply a result of a saving of energy and material which in the more fecund individuals at lower dose rates is spent in egg production.

Here is further evidence that the reduction of fecundity was due to direct effects of the radiation on the cells of the ovaries rather than indirect, physiological effects. When decreased fertility is due to the physiological condition of the animals, it is usually correlated with decreased, rather than increased, growth rates.

To summarize, it was shown how one species' intrinsic rate of natural increase might be affected by increased intensities of continuous radiation. The possible predictive value of this information was indicated. It was shown how the reduction of intrinsic rate was related to underlying changes in the internal properties of a population and, in turn, how these were caused by changes in individual life-history.

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PART IV. ECOLOGICAL TECHNIQUES UTILIZING IONIZING RADIATION

Preface

Some use of ionizing radiation in biological research predated the cumulation of development of the first nuclear reactor under the able leadership of Enrico Fermi on December 2, 1942. However, subsequent to this date we have seen the use of ionizing radiation permiate all types of biological and nonbiological disciplines. During the last 10 to 15 years there has been an increasing literature on radionuclide use in the environmental sciences. Consequently it has been difficult to restrict to a practical number the selecte readings for this section. Specifically we have neglected the use of radionuclides in specific ecological studies, agricultural research, activation analysis, dating and atmospheric transport. However, we have included review papers on use of ionizing radiation in terrestrial, freshwater and marine ecosystems as well as their component parts. Readers interested in a more comprehensive coverage are urged to consult the selected bibliography of Schultz (1969) Ecological Techniques Utilizing Radionuclides and Ionizing Radiation, U.S. AEC report RLO-2213-1.

USE OF RADIOACTIVE TRACERS IN THE STUDY OF INSECT-PLANT RELATIONSHIPS

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Abstract — Résumé — Аннотация — Resumen

USE OF RADIOACTIVE TRACERS IN THE STUDY OF INSECT-PLANT RELATIONSHIPS. In early uses of radioactive tracers in ecological investigations of pests insect, dispersion and migration phenomena were studied with radioisotopes as markers for individual insects. A more recent development is the use of radioisotopes to evaluate insect-plant and predator-prey associations through estimates of food utilization. Biological elimination of radioisotopes, a nuisance in dispersion studies, is being utilized as a measure of feeding rates. In both field and laboratory experimentation, insects are allowed to reach steady-state concentrations of radioisotopes through feeding. Then the rate of intake is equal to the rate of elimination of the radioisotope: (rate of ingestion) = (steady-state amount) × (fractional rate of loss). Measurements of elimination rates (biological half-lives) permit the steady-state concentrations to be translated into intake rate functions.

Food consumption studies have been performed for single-insect-species populations and for multiple-species populations. In a single-species investigation, radiocaesium in a tagged field site was used to estimate the consumption of willow leaves by populations of the beetle Chrysomela knabi. Direct measurements of food consumption made in the laboratory showed good agreement with field estimates of feeding rates based on the radioisotope techniques. Biological half-lives differed for the larval stages and these had to be considered separately. Radioisotopes provided a means of separating overwintering adults from newly emerged ones, through the more rapid elimination of caesium from overwintering adults.

In multiple-species work, the relationship between size of insect and elimination rate was used to derive an average biological half-life for radiocaesium elimination from herbivorous insects in a field site tagged with caesium-137. This average rate, used in conjunction with data on plant and insect biomasses and concentrations of radiocaesium, permitted an evaluation of plant consumption by an entire insect community. Similarly, the utilization of insects as food by predaceous arthropods was estimated from steady-state concentrations of radiocaesium in predators and prey, biomasses, and an average elimination rate.

EMPLOI DES RADIOINDICATEURS DANS L'ÉTUDE DES RELATIONS INSECTE-PLANTE. Dans les premiers travaux écologiques sur les insectes nuisibles effectués à l'aide de radioindicateurs, les chercheurs ont étudié les phénomènes de dispersion et de migration en utilisant les radioisotopes pour le marquage d'individus. Plus récemment, ils s'en sont servis pour étudier les relations insecte-plante et prédateur-proie, en procédant à des évaluations de l'utilisation des aliments. L'élimination biologique des radioisotopes, qui constitue un inconvénient dans les études sur la dispersion, est utilisée dans ce cas comme mesure des taux d'alimentation. Dans les expériences en plein champ ou en laboratoire, on attend que la concentration des radioisotopes ingérés par les insectes parvienne à l'équilibre. Le taux d'absorption des radioisotopes est alors égal à leur taux d'élimination: (taux d'ingestion) = (quantité à l'équilibre) × (taux de pertes fractionnaire). Les mesures des taux d'élimination (période biologique) permettent de traduire les concentrations à l'équilibre en fonctions exprimant les taux d'ingestion.

Les auteurs ont procédé à des études sur la consommation d'aliments dans des populations composées d'une seule espèce d'insectes et dans des populations composées de plusieurs espèces. Dans une étude en plein champ sur une seule espèce, ils ont procédé au marquage par le radiocésium afin d'évaluer la consommation de feuilles de saule par des populations de chrysomèles (Chrysomela knabi). Les mesures directes de la consommation d'aliments faites en laboratoire ont bien concordé avec les évaluations des taux d'alimentation faites en plein champ au moyen des méthodes radioisotopiques. Les périodes biologiques ont été différentes pour les stades larvaires, qu'il a fallu étudier séparément. Les radioisotopes ont permis de distinguer les adultes ayant survécu à l'hiver de ceux qui venaient d'apparaître; en effet, le césium est éliminé plus rapidement par les premiers.

Crossley, D. A., Jr. 1963. Use of radioactive tracers in the study of insect-plant relationships. pp. 43-53. In: Radiation and Radioisotopes Applied to Insects of Agricultural Importance. (Anonymous). International Atomic Energy Agency, Vienna. (STI/PUB/74).

Dans les études portant sur plusieurs espèces, on s'est servi du rapport entre la taille de l'insecte et le taux d'élimination pour établir une période biologique moyenne d'élimination du radiocésium chez les insectes herbivores dans un champ marqué au césium-137. En rapprochant cette moyenne des données relatives aux ensembles biologiques de végétaux et d'insectes et aux concentrations du radiocésium, il a été possible d'évaluer la consommation de végétaux pour toute une population d'insectes. De même, à partir des concentrations à l'équilibre du radiocésium dans les prédateurs et leurs proies, ainsi que dans les ensembles biologiques, et du taux moyen d'élimination, on a évalué l'importance des insectes dans la nourriture des arthropodes prédateurs

ИСПОЛЬЗОВАНИЕ РАДИОАКТИВНЫХ ИНДИКАТОРОВ ДЛЯ ИЗУЧЕНИЯ ВЗАИМНОЙ СВЯЗИ МЕЖДУ НАСЕКОМЫМИ И РАСТЕНИЯМИ. При более раннем использовании радиоактивных индикаторов в экологических исследованиях насекомых-вредителей их рассеяния и миграции изучались при помощи радиоизотопов, которыми маркировались отдельные насекомые. В последнее время получило распространение использование радиоизотопов для изучения биологической ассоциации насекомых и растений, а также хищных насекомых и их добычи, исходя из определения потребления ими пищи. Биологическое выделение радиоизотопов, которое мешает изучению рассеяния насекомых, используется в настоящее время для измерения количества потребления пищи. Как в полевых исследованиях, так и в лабораторных экспериментах насекомым дается возможность достичь в процессе питания состояния устойчивой концентрации радиоизотопов. В этих условиях темп поглощения данного радиоизотопа равен темпу его выделения: (темп поглощения) = (величине устойчивого состояния) x (скорость потери). Измерения темпов выделения (биологического полураспада) позволяют переводить состояния устойчивой концентрации в функции темпов поглощения.

Изучение потребления пищи было проведено как для популяций насекомых одного только вида, так и для популяций смешанного типа. При изучении насекомых одного вида на меченом поле использовался радиоактивный цезий для определения потребления ивовых листьев популяциями жука Chrysomela knabi. Проведенные в лаборатории непосредственные измерения потребления пищи показали хорошее совпадение с результатами изучения темпов питания, полученными на опытном поле на основании радиоизотопного метода. Однако для личинок биологический период полураспада оказался иным, так что эти результаты должны рассматриваться раздельно. С помощью радиоизотопов удалось разделить перезимовавших взрослых особей от вновь появившихся на свет, благодаря более быстрому выделению цезия перезимовавшими взрослыми особями. При работе со смешанными популяциями было использовано соотношение между размером насекомого и темпами выделения радиоизотопов для определения среднего биологического периода полураспада при выделении радиоактивного цезия травоядными насекомыми, меченными цезием-137. Эти средние темпы совместно с данными о биомассах растений и насекомых, а также о концентрациях радиоактивного цезия позволили определить размеры потребления растений всей популяцией насекомых. Аналогичным образом, количество насекомых, съедаемых хищными членистоногими, было определено на основании состояния устойчивой концентрации радиоактивного цезия у хищников и у их добычи, их биомасс и средних темпов выделения.

EMPLEO DE MARCADORES RADIACTIVOS PARA ESTUDIAR LAS RELACIONES INSECTO-PLANTA. Las primeras aplicaciones de los indicadores radiactivos en los estudios ecológicos sobre las plagas de insectos y sobre los fenómenos de dispersión y migración insectiles consistieron en marcar con radioisótopos a algunos insectos. Más recientemente se han llegado a utilizar los radioisótopos para estudiar las relaciones insecto-planta y depredador-víctima a través del consumo de sustancias nutritivas. La eliminación biológica de los radioisótopos, elemento perturbador en los estudios sobre la dispersión, sirve para medir los índices de alimentación. Tanto en las campañas experimentales como en los estudios de laboratorio se logra una concentración estacionaria de radioisótopos en los insectos por ingestión. El índice de ingestión de radioisótopos es entonces igual al de eliminacion; la fórmula aplicada es la siguiente (índice de ingestión) = (cantidad estacionaria) × (índice fraccional de pérdida). La medida del índice de eliminación (período biológico) permite determinar el índice de ingestión a partir de los datos relativos a la concentración estacionaria.

Se han estudiado el consumo de alimentos en poblaciones insectiles formadas por una sola especie y formadas por varias especies. En el estudio de una de las primeras, se utilizó el radiocesio aplicándolo en una zona determinada para calcular el consumo de hojas de sauce por poblaciones del escarabajo Chrysomela knabi. Las medidas directas del consumo de alimentos, realizadas en laboratorio, dieron resultados que coincidían con los obtenidos en las campañas experimentales emprendidas para calcular los índices de alimentación mediante el uso de radioisótopos. En la fase larval, el período biológico de los insectos es diferente, por lo que hubo de ser objeto de un estudio aparte. Los radioisótopos permitieron distinguir a los adultos que habían pasado la hibernación de los adultos nuevos, porque la eliminación del cesio en los primeros era más rápida.

En los estudios sobre poblaciones formadas por varias especies, la relación entre el tamaño del insecto y el índice de eliminación sirvió para calcular el período medio biológico para la eliminación del radiocesio por insectos harbívoros en una zona tratada con ^{137}Ce. Este período medio y los datos sobre las masas biológicas vegetales e insectiles y sobre las concentraciones de radiocesio han permitido calcular el consumo de vegetales de una población entera de insectos. Del mismo modo, se ha podido calcular el consumo de insectos de los artrópodos depredadores basándose en las concentraciones estacionarias de radiocesio en los depredadores y en las víctimas, las masas biológicas y el índice medio de eliminación.

INTRODUCTION

In modern insect-control practices, an integration of chemical, biological, cultural and other manipulative procedures is increasingly visualized as the ideal means for minimizing the depredations of pest insects and mites. From the purely biological aspects, autecological work on pest insects has always been considered meritorious and ecological phenomena were prominent in the attempts at "biological control" during the past few decades. Recent concepts, however, transcend the older ideas of biological control in that pest insects are regarded as members of more extensive ecological systems. For example, SMITH [1] has listed three principles for an integrated control concept which may be restated briefly as follows: (1) Crops, pest insects, and other biota and environment should be treated as a functional unit — the ecosystem; (2) Control measures should aim to keep pests below economic levels rather than attempt complete eradication; and (3) Disruption of other parts of the ecosystem must be considered in the evaluation of control procedures.

Implicit in such concepts is a consideration of insect-crop relationships as part of a unit system and the evaluation of control measures as a shifting of balances within the system. Such an integrated control procedure is not always necessary and may even be undesirable in some instances. The evaluation of even a very effective chemical control procedure must be made on more than destruction of pest insects, however, and such evaluation falls within the realm of ecology.

Radioisotope techniques provide an effective means of studying insect-plant relationships within an ecosystem context, and the full value of these techniques evidently is yet to be realized. Early uses of radioisotopes in economic entomology involved studies of dispersal and migration phenomena [2]. The unique value of radioactive materials as markers for individual insects has become a universally appreciated technique [3]. In mass tagging experiments, the loss of ingested radioisotope due to biological elimination was noted and deemed to be of nuisance value only. DAVIS and FOSTER [4] seem to be the first ecologists to suggest that biological elimination of radioisotopes be used to measure feeding rates, although this concept is inherent in numerous physiological studies [5]. The new doctrine of health physics also has contributed functional models and terminology. Essentially these methods use elimination rates to estimate accumulation rates, so that the concentration of a radioisotope in an insect (for example) can be used to infer rates of plant consumption or prey consumption by predaceous insects. The elimination rate technique offers a widely applicable and uncomplicated means for trophic analysis.

ELIMINATION RATES AND BIOACCUMULATION

The amount of a radioisotope which is retained in an insect following ingestion of a single dose decreases exponentially, because of biological elimination. Fig. 1 shows the retention of caesium-137 by a female grasshopper (Melanoplus differentialis); the exponential decrease produces a straight line in a semilogarithmic graph. Expressions of such rates of elimination are usually made in terms of the biological half-life. This is defined as the time required for the amount of a radioactive element in the body to decrease to one-half its initial value as the result of biological processes. The data in Fig. 1 suggest a biological half-life of approximately 2.5 d. Since these data were not corrected for radioactive decay, the result is technically an effective half-life; however, the physical half-life of Cs^{137} is so long in comparison with the observed half-life (25 yr as against 2.5 d) that radioactive decay can be ignored. In the general case these three rates are related as follows:

$$T_{eff} = \frac{T_b\, T_r}{T_b - T_r} \qquad (1)$$

where T_{eff}, T_b, and T_r are the effective, biological, and radioactive half-lives respectively.

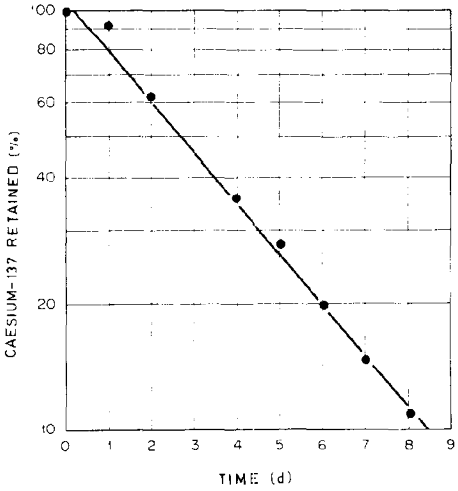

Fig. 1

Retention of Cs^{137} by a single grasshopper, Melanoplus differentialis

By analogy with radioactive decay, the loss of radioactivity from the insect's body can be described from the relationship:

$$A_t = A_0\, e^{-kt} \qquad (2)$$

where A_t is the radioactivity at any time t, A_0 is the initial radioactivity of the insect at time $t = 0$, and k is an elimination constant equal to $0.693/T_b$ (or $0.693/T_{eff}$ in the general case). For the case illustrated in Fig. 1, k is 0.693/2.5 d, or 0.277 d^{-1}.

The amount of radioisotope eliminated during any given day, in this example, is equal to the radioisotope content of the insect times the elimination constant k. Thus when an insect feeds continually on radioactive plants the daily rate of elimination will increase until daily intake is balanced by daily elimination. At that time the concentration of radioisotope in the insect may be said to have reached a steady state. The relation between intake and elimination in a steady state is:

$$r = kA_q \tag{3}$$

where r is the rate of feeding ($\mu c/d$), k is the elimination constant (d^{-1}), and A_q is the whole-body radioactivity (μc) in steady-state equilibrium. Thus, if the steady-state radioactivity of the insects is measured and the biological half-life for the particular radioisotope is known, the rate of feeding r can be calculated directly. If the concentration of radioisotope in the food of the insects is known, then r can be expressed as the amount of food consumed per day. If only a fraction of the radioisotope ingested is assimilated, a correction must be applied. The right-hand side of Eq. (3) may be divided by the fraction assimilated, or the elimination of unassimilated material may be treated as an additional exponential factor. No such correction is necessary for the results discussed in this report since they are based on radiocaesium, which is almost completely assimilated [6].

The approach to the steady-state equilibrium concentration is asymptotic; the time required to reach 50% of the equilibrium value is equal to one biological half-life. Practically, equilibrium is considered to be attained after a time equivalent to five biological half-lives. This would be 97% (31/32) of the final value.

APPLICATION TO FIELD POPULATIONS

Two types of field application of these radioactive tracer methods will be discussed, the single-species population and the multiple-species population, since each presents its own set of requirements.

Single-species population

Feeding rates were estimated for the third-instar larval stage of Chrysomela knabi Brown, feeding upon willow leaves. This beetle species overwinters in the adult stage. Eggs are laid on young willow leaves in early May, in the East Tennessee area. A single generation of beetles develops each year. All three larval stages as well as adults feed exclusively on willow leaves. Development is completed usually by mid-June. The life history of this beetle species has been described by BROWN [7].

Laboratory studies showed that biological half-lives for radiocaesium in this insect increased with age and size during development. Elimination

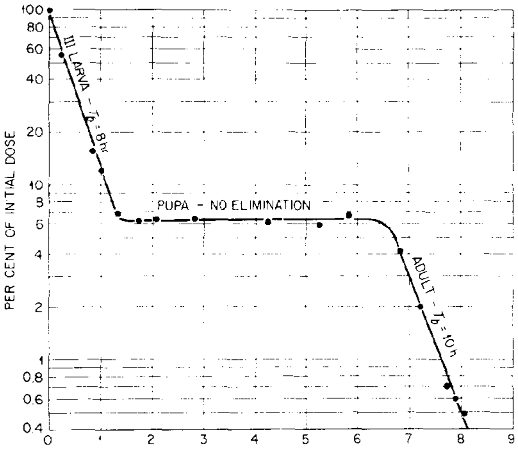

Fig. 2

Retention of Cs^{134} by an individual beetle (Chrysomela knabi)
Third-instar larva, pupa, and adult stages are shown.

of Cs^{134} occurred at rates corresponding to a 7-h biological half-life for first-instar larvae (mean of 4 individuals), an 8-h T_b for second-instar larvae (10 individuals), an 8-h T_b for third-instar larvae (14 individuals), and a 10-h T_b for newly-emerged adults. Fig. 2 illustrates Cs^{134} retention by one individual. Loss during the third instar, no elimination during the pupal stage, and further loss by the newly emerged adult are shown. These short biological half-lives suggest that a steady-state concentration would be reached in less than two days of feeding. However, the average duration of the larval stages also is short, and only during the third instar (5-d average duration) and the adult stage might a steady-state equilibration be expected.

Beetles containing Cs^{137} were obtained from willows growing on the White Oak Lake bed. White Oak Lake was formerly a part of the Oak Ridge National Laboratory's low-level waste disposal system. The lake was drained in 1955, and the plants and animals which invaded the lake basin accumulated various radioisotopes from the sediments [8]. Cs^{137} accumulated by willows (Salix nigra) growing in these sediments is transferred to insects feeding upon these plants. The consumption of leaves was calculated for third-instar larvae, which were more readily collected than were adults. The Cs^{137} content of a sample of 122 third-instar Chrysomela knabi larvae was 72.9 ± 14.6 pc/g dry wt. This value represents the steady-state equilibrium concentration. The elimination constant k, based on a biological half-life of 8 h (= 0.333 d), is estimated as 0.693/0.333 = 2.08 d^{-1}. By substitution in Eq. (3), r = (2.08) (72.9) = 151 ± 30.4 pc/g beetle per day. The average Cs^{137} concentration in willow leaves was 37.8 ± 2.38 pc/g dry wt., on the basis of leaves from which the beetle larvae were collected. Dividing 151 pc consumed per day by 37.8 pc/g gives 4.01 ± 0.84 g plant consumed/g beetle per day. The average weight of third-instar larvae in the sample was 4 mg;

TABLE I

AVERAGE WEIGHTS OF FOOD CONSUMED BY THIRD-INSTAR LARVAE OF CHRYSOMELA KNABI

Values are means for 12 measurements.

Age of larvae (days in third instar)	Mean weight of beetles (mg dry wt.)	Mean weight of food eaten (mg dry wt.)
1	1.9	6.3
2	2.4	10.7
3	4.6	15.0
4	7.4	15.4
5	9.0	5.3

the consumption of willow leaves thus would be estimated at 16.0 ± 3.4 mg dry wt. per beetle larva per day.

Table I shows the results of direct laboratory measurements of food consumption (willow leaves) by third-instar larvae. This instar is a period of rapid growth; weights of larvae increased from a mean of 1.9 mg to 9.0 mg in the 5-d period. Food consumption showed an increase from 6.3 to 15.4 mg/d, followed by a sharp drop to 5.3 mg/d on the day preceding pupation. The average weight of the third-instar larvae collected from willows on White Oak Lake bed was 4 mg; in Table I this corresponds to a daily food consumption of about 15 mg, as compared with the field estimate of 16 mg inferred by the radiocaesium technique.

These results show the accuracy which can be obtained for field data by this radioisotope technique. Biological half-lives are probably slightly different for each day of prepupation in the third larval instar, as well as between instars, but additional refinements in estimates of elimination constants would appear unnecessary. The results may be exceptionally good in this example, since the insects sampled could be related to a particular leaf on which they were feeding and thus sampling error was reduced for estimates of leaf concentrations of Cs^{137}. Had the sampling been based on adults, the motility of that stage might have reduced the accuracy in field estimates. An anomaly in the biological half-lives of Cs^{137} in adult beetles was also noted: the average T_b was 10 h for new adults but only 7.5 h for year-old ones. This difference is probably a reflection of the metabolic status of the beetles. New adults were accumulating materials to prepare for hibernation, whereas year-old ones were mating, seeking oviposition sites and laying eggs. The radioisotope equilibration technique would have estimated different feeding rates for the two groups of adults, other things being constant. Laboratory information was not sufficient to show whether feeding rates really differed for new and year-old adults.

Multiple-species populations

Areas with natural vegetation may easily support several hundreds of different species of insects, and ecological measurements become infinitely more complicated in such communities. Direct measurement of food consumption becomes difficult if not impossible. Indirect estimates must be made if generalizations are to be applied to the entire insect community, and approximate techiques become particularly attractive. The radioisotope equilibration method of Eq. (3) can be applied to multiple-species populations as well as to single-species populations. The rate of plant consumption by the insect community living on the above-mentioned White Oak Lake bed has been estimated through this radioisotope technique by CROSSLEY and HOWDEN [6], and the theoretical validity has been discussed by CROSSLEY [9]. Additional samples of the flora and fauna of White Oak Lake bed, taken during the summer of 1961, form the basic data for the present discussion. The results are similar to the estimates reported previously [6, 9] but some differences noted in the discussions can be ascribed to unusually cool weather in the summer of 1961.

An appropriate value must be selected for the elimination constant k of Eq. (3). Ideally this value would be some sort of weighted average for all of the insect species feeding on vegetation on the White Oak Lake bed. Clearly it is impractical to measure radioisotope elimination rates for each

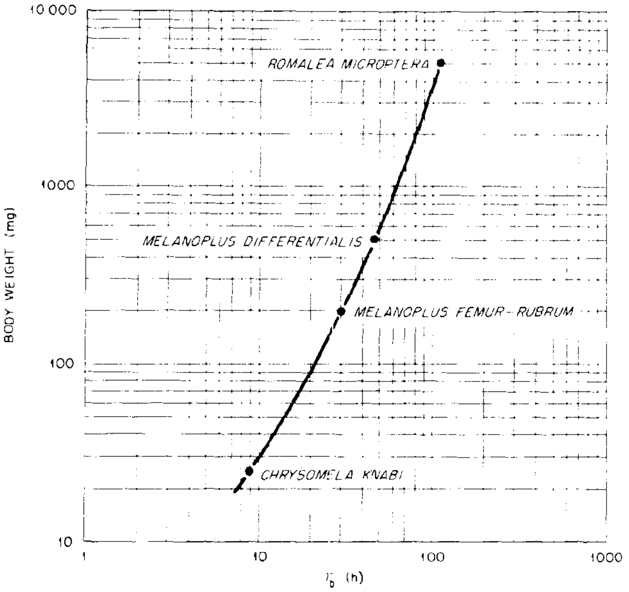

Fig. 3

Relation of insect weight to biological half life of caesium.
(After CROSSLEY [9])

of the several hundreds of species. For caesium, however, the biological half-life has been found to be related to the size of the insect [9]. Fig. 3 shows the biological half-life of caesium in insect species plotted as a function of fresh weight (mg) of the insects. Biological half-lives of caesium in mammal species, as reported by LANGHAM and ANDERSON [10], fall close to a projection of the line in Fig. 3. Weights of insect species can thus be made the basis for selection of an average k for the entire community. For the present discussion we shall use a weighted average weight per insect collected in the 1961 samplings, which was approximately 20 mg fresh wt. The line in Fig. 3 suggests a biological half-life for caesium of about 7.5 h for this weight. This is 0.313 d, and the average elimination constant k is estimated as 2.21 d^{-1}. This is larger than the elimination constant of 0.98 d^{-1} estimated for the 1958 samplings [9] but evidently there was a real difference between the average size of insect in 1958 and that in 1961.

TABLE II

CONCENTRATIONS OF CAESIUM-137 AND BIOMASSES FOR SOIL AND TROPHIC LEVELS OF THE PLANT-INSECT FOOD CHAIN ON WHITE OAK LAKE BED, SUMMER 1961

Mean ± standard error; number of samples in parentheses.

	Caesium-137 concentration (pc/g dry wt.)	Biomass (g/m^2)
Soil	7300 [a]	-- [b]
Plants (leaves)	160 ± 32 (5)	317 ± 42.4 (4)
Herbivorous insects	78 ± 4.8 (5)	0.111 ± 0.0192 (8)
Predaceous insects	73 (8 samples lumped)	0.0117 ± 0.0015 (8)

[a] Soil value based on grand mean from core samples.

[b] No samples taken.

The basic data obtained in the 1961 samplings are given in Table II. Concentrations of Cs^{137} in plants (leaves) and in herbivorous and predaceous insects are essentially the same as those reported for 1958 [6]. Biomasses, however, are lower, evidently as a result of cooler weather in the summer of 1961. Plant biomass dropped from about 600 to about 300 g/m^2; the average herbivorous insect biomass dropped from approximately 250 to approximately 100 mg/m^2. Final biomass samples at the end of the summer approached 250 mg/m^2, however.

Using the data in Table II, one can estimate the average rate of feeding r for the herbivorous insects as follows: (2.21)(78) = 172 pc/g insect per day.

Dividing by plant concentration (160 pc/g), one obtains r = 1.08 g plant/g insect per day. This is 0.120 g plant/m^2 d for a biomass of 111 mg/m^2, or 12 g/m^2 in a 100-d growing season. The proportion of the plant biomass consumed by insects would thus be 3.8%, which compares favourably with the 4% estimate reported for the 1958 data [9].

This amount of plant consumption is the amount necessary to maintain the steady-state equilibrium concentration in the herbivorous insects. A certain amount of the insect biomass is lost through mortality during the season, and is offset (or more than offset) by insect production. This production represents an additional consumption of plants by insects, for which we have no measure in this mixed insect community. However, estimates of feeding for production in various communities are usually about 25% of the amount of feeding required for maintenance [11]. If this is true for the insect community on White Oak Lake bed vegetation, the total average daily consumption of plants would be about 0.150 g, or 15 g per season, or 4.7% of the plant biomass consumed during the entire growing season.

Similar calculations can be made for predaceous insects from the data in Table II. If all of the predators are assumed to feed on herbivores, and thus secondary predation is ignored, r can be estimated as 2.06 g herbivore consumed per g predator per day, or 0.024 g herbivore consumed/m^2 d, or 2.4 g herbivore consumed/m^2 per growing season. This value is 15% of the amount of plant material consumed by the herbivorous insects, but 80% of the total insect production estimated above. These estimates of herbivore consumption by predators seem high. However, TEAL [12], in discussing the predator-prey balance in a temperate cold spring, estimated non-predatory mortality of herbivores at 19.4%, which is the converse of the 80% predatory mortality estimated here. The relative paucity of predaceous insects makes sampling more difficult for both Cs^{137} content and biomass estimates. Further sampling and analysis of the predator trophic level will be required to improve estimates of food consumption by predators.

DISCUSSIONS AND CONCLUSIONS

The field aspects of the two examples given here were handled under conditions unfavourable for radioactive tracer work. White Oak Lake bed contains a mixture of heterogeneously distributed radioisotope species, at levels of radioactivity generally lower than is desirable for tracer studies. These difficulties have been overcome in newly created tagged field sites. Insect consumption of foliage in a forest site tagged with Cs^{137} is being measured in a manner similar to the studies performed on White Oak Lake bed, except that control over distribution and concentration of caesium-137 in the forest system has greatly eased the problems of measurement. The accumulation of various radioisotopes by forest-floor arthropods also is being studied through steady-state concentrations and biological half-lives. In this case tagging has been accomplished by placing tagged tree leaves in small fenced (1-m^2) plots. The arthropod food chain which has as its base leaf litter is being studied in this manner.

Preliminary results from these additional studies have confirmed the value of measurements of biological half-lives for the interpretation of food-chain transfer of radioisotopes. These radioisotope techniques are fulfilling their initial promise as an uncomplicated technique for specifying rates of movement of materials along food chains, and thus quantifying the relationships of herbivorous insect populations to plants and of predators to prey.

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USE OF RADIONUCLIDES IN ECOLOGICAL STUDIES OF INSECTS

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INTRODUCTION

Ecological knowledge about insects is fundamental and required for their effective control. The most successful method of controlling important pest insects depends on an understanding of their entire life history, food habits, dispersal, mating, behavior, parasites, predators, and other ecological aspects. Then economic control can be carried out by capitalizing on the weakest link or most vulnerable point using quarantines, environmental control, insecticide treatment, irradiation sterilization, baits, traps, and predators or parasites, or a combination of these. Studying the ecology of many insects frequently involves prolonged field studies and requires efficient techniques and methods. This is often complicated by insect behavior at night, underground, or in inaccessible places. An effective marking method is needed.

Radionuclides have been of value in labeling and studying the dispersal and movement, migration, life history, and behavior of underground insects, orchard and forest insects, honey bees, and various species of crop insects. These tracers have been helpful in elucidating the role of insects in transmitting disease organisms to plants, animals, and human beings. Ecological studies have been carried out with radionuclide-labeled flies, ticks, mosquitoes, and other insects that transmit diseases or are important pests. Use of radionuclides has contributed to the study of parasites and predators of disease vectors. They have been of value in ecological studies on food chains, nutrition cycles, and population studies.

The use of radionuclides in studying insects has increased rapidly. In 1950 only about 50 papers had been published where this technique was used. Today approximately 1,300 papers have appeared, with about 400 involving insect ecology. Many new uses for radionuclides with insects are being discovered and more valuable ecological data can be expected. Ecological studies involving insects are being carried out in about 30 countries in the world, with local emphasis being placed on the most important pest species. An attempt is made to review some of the more important ecological studies of insects using radionuclides. A comprehensive review is impossible here because of space limitation. The different radionuclides used and methods of application are also discussed.

SELECTION OF RADIONUCLIDES AND LABELING INSECTS

About 44 different radionuclides have been used in studies involving insects. In addition a number of stable nuclides such as deuterium have been used for various purposes. In selection of suitable radionuclides for tagging insects, the following factors must be considered: (a) type of radiation, (b) energy of radiation, (c) half-life of the radionuclide, (d) biological accumulation and retention in the insect (if labeled internally) and the biological half-life, (e) toxicity to the insect, (f) the form of the radionuclide, and (g) the ease of handling, labeling, and detecting the radionuclide.

The radionuclides that have been used successfully for labeling or marking insects for ecological and biological studies include carbon-14, sodium-24, phosphorus-32, sulfur-35, chlorine-36, calcium-45, scandium-46, cobalt-60, zinc-65, strontium-89, iodine-131, cerium-144, irridium-192, gold-198, radium-226, and thorium-(230?). Various radionuclides have been found to be toxic at levels used in certain insects, such as calcium-45, iron-59, rubidium-86, silver-110, cadmium-115, and iodine-131. Some radionuclides are not retained, such as calcium-45 and zirconium-95, and others are unsuitable for other reasons: carbon-14, sulfur-35, chlorine-36, and iodine-131. The use of one radionuclide for one species of insect may be very suitable, while for another it may be impractical. The most commonly used radionuclides for ecological studies are the beta emitters, phosphorus-32 and strontium-89. These have advantages of suitable half-lives, effective incorporation and retention in the insect, low toxicity, ease of detection and handling, and relatively low cost. For many insect ecology studies, certain beta emitters are most suitable since they are easier to handle. Those that have been used effectively include phosphorus-32, sulfur-35, chlorine-36, calcium-45, strontium-89, and cerium-144 (cerium-144 is also a weak gamma emitter). These nuclides do not permit location of insects from a suitable distance with the quantities usually used for labeling. However, for location of insects underground, in and under debris, under bark, and in trees, a strong gamma emitter is required. The gamma emitters successfully used for labeling insects include scandium-46, cobalt-60, zinc-65, iodine-131, iridium-192, tantalum-182, gold-198, radium-226, and thorium-(230?). Some of these radionuclides also emit beta or alpha particles.

Many methods have been developed for marking insects with radionuclides. These include contamination of insect food, of growth medium, of external surface of the insect, or injection. Insect food has been contaminated by soaking the food, by injecting radionuclides into animal hosts, by contaminating drinking water, milk, sugar solutions, and by injecting insect food plants or growing them in contaminated media. Insects have been labeled by growing them in a contaminated medium such as organic substrate for flies, water for mosquitoes and other aquatic insects, in labeled animals for screw worm flies, and labeled plants. Many methods have been used for external labeling including dipping, painting, spraying, attaching clips or wires of radioactive materials, and treating the surface with wetting or adhesive agents. Radionuclides have been injected or perfused as liquid, or inserted as a piece of metal or other substance into the body of the insect. In addition, insects have been exposed to labeled gases that are taken up and accumulated in the body.

FOREST AND ORCHARD INSECTS

Forest and orchard insects have been labeled to determine dispersal and movement, overwintering sites, longevity, and location of the insects at given times (Table 1). This has been facilitated by use of gamma emitters which can be located at greater distances. Insects have been labeled in a variety of ways for dispersal studies. Englemann spruce beetles were dipped in an iodine-131 alcohol solution that gave good concentrations for a relatively short period (Davis and Nagel, 1956). White pine weevils were labeled with cobalt-60 nitrate dissolved in cellulose acetate and acetone to form an adhesive attached to the wings of the beetle. Of 64 beetles labeled, 33 per cent were alive after two months, the same as unlabeled controls. The labeled insects could be detected from a distance

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Table 1. Dispersal of radionuclide labeled forest and orchard insects.

Insect	Nuclide	Number released	Recovery and longevity	Maximum dispersal (kilometers)	Source
Pissodes strobi (white pine weevil)	Cobalt-60	64	33 per cent in 60 days		Sullivan (1953)
Pissodes strobi (white pine weevil)	Scandium-46	1,600	60 to 70 per cent, to 8.5 months	0.22	Godwin et al. (1957)
Dendroctonus pseudotsugae (Douglas fir beetle)	Phosphorus-32				Fang and Allen (1955)
Dendroctonus frontalis (southern pine beetle)	Iridium-192	20,000			Speers (1956)
Dendroctonus engelmanni (Englemann spruce beetle)	Phosphorus-32 Iodine-131	19,000	5 per cent to 14 days		Davis and Nagel (1956)
Dendroctonus engelmanni (Englemann spruce beetle)				4.8	Beal (1958)
Rhyacionia buoliana (European pine shoot moth)	Cobalt-60	104	42.9	0.046	Green et al. (1957)
White grubs	Tantalum-182	movement in soil			Speers (1956)
Conotrachelus nenuphor (plum curculio)	Phosphorus-32	62	to 120 days	0.11	Rings and Layne (1953), Rings (1954)
Conotrachelus nenuphor (plum curculio)	Cobalt-60	705	to 8.5 months	0.27	Rings and Layne (1953), Rings (1954)
Conotrachelus nenuphor (plum curculio)	Zinc-65	23	to 120 days	0.041	Rings and Layne (1953), Rings (1954)
Conotrachelus nenuphor (plum curculio)	Strontium-89	175	3 days	0.123	Rings and Layne (1953), Rings (1954)
Conotrachelus nenuphor (plum curculio)	Iodine-131	86		0	Rings and Layne (1953), Rings (1954)
Dacus dorsalis (oriental fruit fly)	Phosphorus-32		to 40 days		Roan (1952)
Drosophila melanogaster (fruit fly)	Phosphorus-32	20,000		3.84	Warner (1959)
Ceratitis capitata (Mediterranean fruit fly)	Phosphorus-32	944		32.0	Christenson and Foote (1960)
Rhagoletis cingulata (cherry fruit fly)	Phosphorus-32	2,010	to 42 days	0.287	Jones and Wallace (1955)
Rhagoletis completa (walnut husk fly)	Phosphorus-32	15 percent of natural population		14.4	Barnes (1959)

of 2.7 meters (Sullivan, 1953). The Douglas fir beetle was labeled with phosphorus-32 by Fang and Allen (1955) by feeding phosphorus-32 in sugar solution. White pine weevils labeled with scandium-46 in 20 per cent alcohol could be detected at 1.5 meters. The longevity, flight range, direct uninterrupted flight range, and practical control methods were determined from the releases by Godwin et al. (1957). The southern pine beetle was labeled with iridium-192 and released in isolated areas infected with beetles (Speers, 1956). Female European pine shoot moths *Rhyacionia buoliana* were labeled with cobalt-60 by painting the radionuclide on the abdomen (Green et al., 1957). The labeled insects could be located at one meter. Of the 104 moths released, 42.9 per cent were recovered. The moths stayed in the pine stand where they were released, and they dispersed normally to 46 meters per flight. The moths were decimated by birds and other predacious animals. The radiation from 25 to 50 microcuries of cobalt-60 apparently did not affect the moths adversely.

The leaf miner moth *Phyllocnistis labyrinthella* was labeled in the adult stage by feeding phosphorus-32 in sugar water. The adults could be located at 0.5 meter. When 200 moths were released they dispersed and were later located, mostly underground where they hibernated. They were located from August to September 30 when the experiment ended (Sundby, 1958).

Peach orchards are seriously damaged by the plum curculio *Conotrachelus nenuphor*. This beetle was successfully labeled with phosphorus-32, cobalt-60, zinc-65, strontium-89, and iodine-131 by Rings and Layne (1953) and Rings (1954). Strontium-89 fed to the beetles in plant tissue or solution was the best label. Of 473 beetles released, 193 recoveries were made at an average of about 25 meters and up to a maximum of 123 meters from the release site. Hibernation of the beetles was studied and they were collected up to 287 days after labeling and release. The cherry fruit fly *Rhagoletis cingulata* was labeled by feeding the adult flies phosphorus-32 in sugar solution by Jones and Wallace (1955). Of 2,010 flies released, 39 were recovered, 37 within 139 meters and a maximum of 287 meters for a period up to six weeks after labeling. Oriental fruit flies *Dacus dorsalis* were labeled by growing larvae in carrot medium containing phosphorus-32, and by feeding adults on a sugar solution containing phosphorus-32. Both techniques produced good radioactivity of the adult flies for over 40 days (Roan, 1952). The Mediterranean fruit fly *Ceratitis capitata* marked with phosphorus-32 dispersed nearly 3.2 kilometers, and seven per cent of 944 marked flies were recovered 1.2 and 2.4 kilometers away. A marked male was recovered 32 kilometers away, including travel over 14.4 kilometers of open sea (Christenson and Foote, 1960).

About 20,000 fruit flies *Drosophilia melanogaster* were labeled by feeding phosphorus-32 spread on fermenting figs. The flies dispersed from a garbage dump 2.24 kilometers into the direction of the prevailing wind to fig orchards. In another release the flies flew 3.84 kilometers in two days (Warner, 1959). The walnut husk fly *Rhagoletis completa* was labeled by spraying an attractant, corn protein hydrolyzate and phosphorus-32, on branches of foliage in a walnut orchard. About 15 per cent of the natural population of flies were labeled with phosphorus-32 and were shown to disperse up to 1.4 kilometers in three weeks. The fly eggs deposited in walnut fruit were found to contain phosphorus-32 (Barnes, 1959).

CROP INSECTS

Tracing the dispersal and underground movement of soil insects such as wireworms and cutworms requires use of a gamma-emitting radionuclide that can be detected through several centimeters of soil. Adult wireworm beetles Agriotes sp. were first tracked by Tomes and Brian (1946) using a radium-226 disc below the wing of the beetle. For labeling the immature stages, an internal label is required, which remains and is not excreted. This was partially solved by inserting a cobalt-60 wire in the larvae (Arnason et al., 1950; Fuller et al., 1951) to label a species of wireworm and two species of cutworms to study their response to moisture, food, and temperature. In Russia, Lebedev (1950) studied movement of soil-inhabiting insects by labeling with radionuclides. Cherepanov and Volgina (1954) showed that Agriotes obscurus moved five meters in three days in loose sandy loam, but only 0.5 meter in solid podzol overgrown with grass. The most successful technique employs a gold-plated cobalt-60 wire attached to the wireworm. (Fredricksen and Lilly, 1955). This was used in studying the effects of insecticides in reducing movement and in killing wireworms. A very interesting automatic Geiger tube detection device has been made that continuously follows, tracks, and records the position of the wireworm through 11.4 centimeters of soil. (Spinks, 1955; Green and Spinks, 1955).

A species of white grub infesting forest trees was labeled with the gamma emitter tantalum-182 by Speers (1956). The radionuclide was introduced as a wire in the grub, and movements of the larvae through the soil were studied.

Various species of crop insects have been labeled to study their dispersal, movement, behavior, and longevity. Many plant-sucking insects have been labeled by allowing the leaf hoppers, psyllids, aphids, and plant bugs to suck up plant sap containing phosphorus-32. Most of these studies have been concerned with transmission of plant disease instead of dispersal. Bean aphids and green peach aphids became labeled from feeding on broad bean and sugar beet plants watered with $Na_3P^{32}O_4$ solution. The movement of the aphids Myzus persicae and Aphis fabae in the field and their relation to spreading sugar beet yellows was studied by Bjorling et al. (1951). Mealy bugs (Pseudococcus sp.) were fed on phosphorus-32 in cacao seedlings by Cornwell (1956) in studies relating to mealy bug behavior and control of virus disease of cacao in the Gold Coast.

In a study of coccinelid beetle larval behavior, small wires of tantalum-182 were glued to the prothorax of newly hatched larvae, increasing the weight by 24 per cent, but the behavior while crawling on plants was apparently normal (Banks, 1955). The larvae of the lepidoptera Panaxia dominula and Arctia caja were fed on plants treated with sulfur-35. The larvae were labeled and after six to eight weeks the resulting adults showed increased radioactivity (Kettlewell, 1952). The labeling was successful for studying population size, larval death rates, and dispersal activity.

The cotton boll weevil Anthonomus grandis was labeled by dipping the adult beetles in a water solution of cobalt-60 chloride containing a wetting agent (Tergitol 7). The resulting adults showed an average count rate of 4,690 counts per minute before washing and 3,523 afterward. A cotton plant stem was immersed in cobalt-60 solution and the leaves and especially the cotton in the immature bolls became labeled. Large numbers of boll weevils have been marked for use in field studies (Babers et al., 1954).

The mealworm Tenebrio moliter and tobacco hornworm Protoparce quinquemaculata were fed or injected with $As_2{}^{76}O_3$, by Morrison and Oliver (1949) and cabbage and turnip maggot flies were labeled with phosphorus-32 by Oughton (1951) by applying phosphorus-32 around turnip plants. The cabbage maggot Hylemya brassicae adults were fed phosphorus-32 labeled sugar solution with excellent results. Spraying adults with phosphorus-32 was not a suitable procedure (Foott, 1955). Of 1,854 labeled adults released, only two were recovered. Larvae of the cabbage butterfly Pieris rapae crucivora were fed cabbage smeared with calcium-45 and phosphorus-32. Calcium-45 was found in the blood of the adults and was found deposited in white scales on the wings of males. Nematodes and fungus grown from the larvae were labeled (Yagi, 1958).

Adult stinkbugs Eurygaster labeled with cobalt-60 or phosphorus-32 were released. Migration to forests for overwintering occurred in the fall. The bugs migrated 0.5 to 3.0 kilometers west and 10 to 12 kilometers east to a forest at a rate of 0.5 kilometer in 24 hours. After overwintering they congregated, or some dispersed up to 15 kilometers (Andreev et al., 1960). Adult grain moths Hadena basilinea were attracted to lights and then fed on attractant solution containing phosphorus-32 or cobalt-60. Larvae of the moths fed on radioactive grain or were sprayed with radionuclide solution. The adult female moths dispersed in a radius of two kilometers and the males three kilometers (Andreev et al., 1960). The grain moth parasite flies Pseudogonia cinerascens were attracted to baits where they were labeled with phosphorus-32 or cobalt-60. They then dispersed up to 19 kilometers, indicating greater mobility of the parasite than of the host moth.

Two species of grasshoppers, Melanoplus m. mexicanus and Camnula pellucida, were made radioactive by feeding them on phosphorus-32 sprayed plants. At first the rate of loss of phosphorus-32 from excretion was high, but a low level was retained for 28 days through the nymph to adult stage (Fuller et al., 1954). The dispersal of these species of grasshoppers was studied and 20,000 nymphs and adults were fed on wheat seedlings sprayed with 0.5 microcuries of phosphorus-32 in 50 milliliters. When released on bare cultivated fields, they showed no ability to orient or to move toward a food supply. The average rate of movement was 6.4 meters per hour at 70° Fahrenheit, and after six days the total movement of up to 220 meters was random, plus a response to wind directions (Riegert et al., 1954; Spinks, 1954). The grasshopper Melanoplus m. mexicanus was labeled by feeding phosphorus-32 in bran and molasses. About 8,000 third and fourth instar nymphs and 7,500 adults were released in a field of alfalfa, timothy, and weeds. Twenty days after release of nymphs, 43 per cent were recaptured at 9.2, 39 per cent at 18.4, and 18 per cent at 27.6 meters from the release point. At 18 days after release of adults, 56 per cent were recaptured at 9.2, 36 per cent at 18.4, and nine per cent at 27.6 meters from the release point (Baldwin et al., 1958).

The locusts, Locusta migratoria and Locustana pardalina, were labeled with phosphorus-32 in the nymph and adult stages by feeding phosphorus-32 treated bran or hydroponic corn or grass. Adults were also sprayed and could be detected at a distance of 25.4 centimeters after two weeks, but no dispersal studies were carried out (Kettlewell, 1955). It is suggested that locusts be fed or treated with scandium-46, cobalt-60, or other gamma-emitting radionuclides so that they can be located at a distance at night to rapidly determine their dispersal and migration.

Table 2. Dispersal and flight range of radionuclide-labeled mosquitoes.

Species	Locality	Number of mosquitoes released (times 1000)	Per cent recovery	Maximum flight range (kilometers)	Source
Aedes aegypti	Nigeria	276	0.11	1.2	Bugher and Taylor (1949)
Aedes communis	Churchill	3,000	0.005	1.6	Jenkins and Hassett (1951)
Aedes flavescens	Saskatchewan			0.16	Shemanchuk et al. (1953)
Aedes flavescens	Saskatchewan	415	0.02	10.5	Shemanchuk et al. (1955)
Aedes nigromaculis	California	400	0.12	3.0	Thurman and Husbands (1951)
Aedes spencerii	Saskatchewan			0.023	Shemanchuk et al. (1953)
Aedes taeniorhynchus	Florida	1,000	0.03	32.0	Provost (1952)
Aedes taeniorhynchus	Florida	1,560	0.12	40.0	Provost (1957)
Aedes taeniorhynchus	Georgia	2,000	0.023	32.6	Bidlingmayer and Schoof (1957)
Anopheles bellator	Brazil	3		0.8	Aragao et al. (1953, 1956)
Anopheles gambiae	Tanganyika	62	0.95	4.6	Gillies (1961)
Culex tarsalis	California	10		1.6	Thurman and Husbands (1951)
Psorophora confinnis	Arkansas	50	0.09	9.6	Quarterman et al. (1955)
Psorophora discolor	Arkansas			2.4	Quarterman et al. (1955)

SOCIAL INSECTS

Studies have been carried out with honeybees to determine their flight range, mixture with other hives, territoriality, and relationships between the workers, drones, and queen. Drone honeybees were shown to take carbon-14 labeled glucose in syrup through a screen from worker bees in another cage, even when syrup was available in the cage containing drones (Oertel, 1953). The workers showed an average count rate of 9,420 counts per minute per bee, and they passed syrup through the screen to drone bees that accumulated an average of 456 counts per minute per drone.

The continual exchange of nourishment between worker bees was studied by Nixon and Ribbands (1952). It was shown that exchange of sugar syrup containing phosphorus-32 was very rapid. After 27 hours, 43 to 60 per cent of the bees of a hive contained considerable phosphorus-32, which was distributed from only a few workers. After 48 hours, 100 per cent of the larvae in the hive were labeled.

Exchange of nourishment and dispersal were studied by Courtois and Lecompte (1958) using gold-198. When fed as a colloidal suspension in syrup, 100 per cent of the bees were labeled in 24 hours and it was possible to detect the foraging bees at a distance of 10 to 60 centimeters with a scintillometer. In a larger experiment with 40,000 bees, 90 per cent were labeled in 12 hours, and 100 per cent after one day. The exchange of food in the hive was rapid. Some bees of one hive were discovered in nearby hives. The maximum dispersal of marked foraging bees was 1.1 kilometers from the hive. A comparison was made of labeling bees with phosphorus-32 and a genetic marker "cordovan" in showing dispersal of foraging honeybees by Levin (1960). The phosphorus-32 label was fed in syrup and was taken up by nearly all bees in the hives. The phosphorus-32 labeled bees were found 1.6 kilometers east and 2.6 kilometers northeast, and the cordovan bees 1.6 kilometers east and 1.1 kilometers northeast.

Queen bees which have to be checked at intervals in hives have been labeled by an external paint label containing 0.5 microcuries of cobalt-60 per queen. The queen is quickly located in the hive by a Geiger counter and the method is effective. The possible radiation damage was not determined (Raudszuz, 1958).

Manganese-52, -54, and -56 have been used to study the accumulation of manganese by social wasps (Bowen, 1948, 1950). Manganese was accumulated by larvae and extensively lost at pupation, but adults were found to accumulate it particularly in the midgut epithelium, greatly in excess of any known metabolic usage. Barium-140 was shown by Bowen and co-workers (1949, 1951) to be accumulated in hornets and ants even when exposed to infinitesimal amounts. This suggested their use as detectors for radioactive barium leaks not otherwise detectable. Barium-140 decays to lanthanum-140, which in turn goes to stable cerium-140. Such decay chains offer means of studying non-metabolites in organisms by selection and introduction of the proper precursors.

In studies on food transmission between ants, single workers in several laboratory colonies of five species were fed iodine-131 in honey. The workers fed first passed it on to other workers and finally to larvae and queens (Wilson and Eisner, 1957). There was limited food transmission in *Pogonomyrmex badius* to rapid transmission and colony saturation in *Crematogaster lineolata* (Eisner and Wilson, 1958). In mounds of the ant *Lasius minutus* phosphorus-32 labeled honey was passed to other workers, and larvae within eight hours. Ants in adjacent mounds became labeled, indicating that single colonies consist of one or more mounds connected below surface of the ground (Kannowski, 1959). Honey dew gathering ants were studied by labeling aphids on a phosphorus-32 injected thistle plant (Pendleton and Grundmann, 1954).

INSECTS AFFECTING MAN AND ANIMALS

Several species of mosquitoes have been labeled and dispersal studies have been carried out with 11 species in North America, South America, and Africa. The radionuclides phosphorus-32, sulfur-35, strontium-89, and cerium-144 have been used in larval growth media, feeding adults on labeled sugar solution, plants, or animals, or external labeling of the adults by dipping, spraying, or painting the radionuclide. The increased uptake in *Culex pipiens* of strontium-90 and decreased accumulation from normal of ruthenium-106, cesium-137, and cerium-144, which are important fission products, has been shown by Getzova et al. (1960) using "biocomplexon" or the chelating agent EDTA (sodium salt of ethylene-diamine tetraacetic acid). EDTA was shown to accelerate desorption of ruthenium-106, cesium-137, and cerium-144, but increased retention of strontium-90 (Getzova, 1960).

The studies on dispersal of mosquitoes have been summarized in Table 2. Many other studies have been carried out on the behavior of mosquitoes. At Churchill, Canada, during radionuclide labeling studies by Jenkins and Hassett (1951) the abundant pest mosquito *Aedes communis* was shown to consist of two races. One race was shown not to bite human

Table 3. Dispersal and flight range of radionuclide-labeled flies.

Locality	Habitat	Number of flies released (times 1000)	Per cent recovery	Maximum flight range (kilometers)	Source
Musca domestica (housefly)					
Oregon	rural	36	4.6	19.2	Lindquist et al. (1951)
Oregon	rural	54	2.78	32.0	Yates et al. (1952)
Arizona	city	31	0.73	4.8	Schoof et al. (1952)
Arizona	city	56	0.51	8.0	Schoof et al. (1952)
Arizona	city	342	1.8	14.4	Schoof and Siverly (1954a)
Georgia	rural	13.5	8.0	13.1	Quarterman et al. (1954b)
Georgia	city	40	0.24	12.2	Quarterman et al. (1954a)
Russia	rural			12.0	Shura-Bura (1957)
Phormia regina (blowfly)					
Oregon	rural	1.2	14.0	12.8	Lindquist et al. (1951)
Oregon	rural	60	2.64	44.8	Yates et al. (1952)
West Virginia	city	16	0.06	16.5	Schoof and Mail (1953)
Georgia	city			6.4	Quarterman et al. (1954a)

beings. This has a potential importance in natural control by introducing and substituting a non-biting race or strain into an ecological niche for a harmful pest. This replacement could be carried out concurrently with introduction of radiation-sterilized males of the biting race.

The dispersal of radio-labeled houseflies has been studied in several areas and the data have been compiled by Jenkins (1957). They show (Table 3) that the houseflies fly a maximum distance of 32 kilometers and frequently 15 kilometers. Blowfly populations disperse up to 45 kilometers and various other flies have been found to disperse widely.

The primary screw worm *Callitroga hominivorax* was labeled by Radeleff et al. (1952) by rearing larvae in a meat medium containing phosphorus-32, or in wounds of living sheep or goats injected with phosphorus-32. The emerged adults were well labeled, and 10,000 were released for field studies. Five species of blackflies were labeled with phosphorus-32 by Fredeen et al. (1953) in Saskatchewan. Colonies of labeled larvae and pupae were found over 0.4 kilometer downstream from the point of release, and an adult was recaptured 90 meters from the stream. About 90,000 eye gnats *Hippelates pusio* were fed phosphorus-32 in honey and released in two tests, 0.8 and 1.6 kilometer distance from a small town. In both tests there was almost complete penetration of the small town on the day of release. Labeled eye gnats were collected over 1.6 kilometers from the release site in 3.5 hours (Dow, 1959).

Fleas *Xenopsylla cheopis* and *Nosopsyllus fasciatus* were labeled with carbon-14 in glycine and acetic acid externally, and by feeding on injected rodents. External application lasted two months, and internal, from feeding on rodents, lasted five months (Novokreshchenova et al., 1961).

Dispersal studies have been carried out by phosphorus-32 labeling of the lone star tick *Amblyomma americana* in Texas. The ticks were soaked in phosphorus-32 suspension; the addition of a wetting agent did not increase uptake or retention but did reduce survival and is not recommended (Knapp et al., 1956). Ticks *Ixodes* sp. were tagged with cerium-144 by bathing them in radionuclide solution for five minutes (Quan et al., 1957). *Ixodes ricinus* were labeled with carbon-14 in glycine that was injected in mice and rabbits. Following feeding by the ticks the carbon-14 persisted through molting to over seven months (Babenko, 1960).

The blood-sucking bug *Triatoma protracta* was labeled by applying one lambda of cerium-144 in a solution with one microcurie per milliliter on the backs of the bugs (Quan et al., 1957). The nymphs of the bugs *Triatoma infestans* and *Panstrongylus megistus* were labeled by injection of thorium-nitrate into the abdomen, and by feeding adult bugs on a pigeon previously inoculated with thorium-(130?). The resulting adult bugs were labeled (Aragao, 1954).

Cockroaches are a bad pest insect, especially in homes and buildings. While they have been implicated in transmitting most diseases, proof of this is available for almost none. Radionuclides offer a method for determining the part they play in the epidemiology of various diseases.

The American cockroach *Periplaneta americana* was labeled with phosphorus-32 and released in sewer manholes in Phoenix, Arizona, by Schoof and Siverly (1954b). Of 6,500 released, 906 recaptured roaches indicated no significant movement in the sewerage system in 8.5 weeks. One labeled roach was trapped in a yard 20 meters away from the release site. A dispersal study in Texas showed widespread labeled roach dispersion from sewer manholes into adjacent homes (Anonymous, 1953). American roaches were sprayed with phosphorus-32 and casein as an adhesive. When roaches native to the manholes were labeled and returned there was little movement, about ten meters into a yard and 55 meters down the sewer. When 1,200 non-native roaches were labeled and released in manholes they were found in a kitchen 26 meters away and over 110 meters away in the sewerage system (Jackson and Maier, 1955). They were considered as potential vectors of *Salmonella* infections to man. An attempt was made to label American roaches with the gamma-emitter zirconium-95 that would enable the detection of roaches at a distance. Following injection of the roaches it was found that zirconium-95 was not retained (Jenkins and Hassett, 1950). The German roach *Blatella germanica* was successfully labeled by painting cerium-144 externally on the backs of the roaches (Quan et al., 1957). Black and reddish roaches were labeled by giving them phosphorus-32 in their food (Ludicke, 1954), and German roaches *Blatella germanica* by giving phosphorus-32 in rye biscuits for 48 hours (Khudadov, 1959).

PARASITES AND PREDATORS

The habits, life histories, and epidemiological role of many important ectoparasites of vertebrate animals are inadequately known. Ticks, mites, fleas, lice, and other medically important ectoparasites require more detailed ecological studies. Use of a tracer technique should provide information on the length of time ectoparasites remain attached to their hosts under natural conditions, whether they change to other hosts, where they are located while unattached, longevity, dispersal, and population size. Labeling of these ectoparasites is quite simple since the host animal can be labeled as desired. White rats and rabbits were injected with phosphorus-32 by Jenkins and Hassett (1950) so that female Aedes aegypti would take up amounts giving 760 to 1,073 counts per minute of phosphorus-32 per blood meal. Rats were injected with 375 microcuries of phosphorus-32 by Yates et al. (1951). After taking a blood meal, Aedes sticticus and Aedes vexans showed count rates of 544 to 897 counts per minute.

The relationship between pathogens and parasites to the infected hosts offers a real opportunity for effective use of radionuclides. Rickettsiae, bacteria, protozoa, and fungi have been effectively labeled with a variety of radionuclides. The relationship of malaria protozoans including sporozoite rates of labeled mosquitoes have been studied (Gillies, 1961). Radionuclides are of value in studying the parasitic relationships of parasite to host. A species of mite was found to be parasitic rather than commensal in habit when the mites became radioactive after feeding on roaches that had been fed on sodium chloride (Cunliffe, 1942). Parasitic Habrobracon wasps became labeled when they actively parasitized phosphorus-32 labeled hosts. The ingested phosphorus-32 had no observed effect on the longevity of the parasites (Grosch and Sullivan, 1954). Mermithid nematode parasitic worms emerging from labeled arctic mosquito larvae were labeled and enabled identification of specific nematode worms under field conditions (Jenkins, 1954).

Although no viruses are presently known to be effective against medically important insects, the effect of radiation from a radionuclide in or on the virus is of interest. Polyhedral virus suspended in carbon-14 labeled alanine and glycine was injected into silkworm larvae. It was concluded that the beta radiation inhibited virus multiplication and 40 per cent of the larvae developed to adults. The labeled polyhedral bodies gave 1,300 counts per minute per milliliter and the virus particles liberated from the polyhedral bodies gave 3,800 (Bergold, 1954).

Natural control of insects by predator insects eating pest insects is important; for example, lady bird beetles have been used economically to control scale insects in California. Field observations to prove the importance of certain predators in controlling injurious insects is frequently a tedious job, especially if the insects are nocturnal, underground, or inconspicuous. When a pest insect is labeled with a radionuclide, after being eaten it leaves the radionuclide in the predator. Chinese praying mantises became well labeled when they were fed on fruitflies and yellow fever mosquitoes labeled with phosphorus-32 (Jenkins and Hassett, 1950). Large dytiscid beetles became labeled after feeding on phosphorus-32 labeled larval arctic mosquitoes. Frogs and several species of spiders became labeled after eating labeled adult mosquitoes, and several species of water beetles and bugs, dragon fly damsel fly, and other aquatic insects became labeled after eating labeled mosquito larvae (Thurman and Husbands, 1951; Jenkins and Hassett, 1951). In detailed studies on predation, Baldwin et al. (1955) showed that phosphorus-32 labeled mosquito larvae decreased in numbers with an increase in predator numbers, and with an increase in percentage of predators that were labeled from consuming phosphorus-32 labeled mosquito larval prey. This technique was made quantitative by Pendleton (1952) so that the exact number of mosquito larvae eaten by a predator could be counted. Labeled blackfly larvae were put in a stream and were fed upon by various predatory stream-inhabiting insects, which became radioactive (Fredeen et al, 1953).

INSECT TRANSMISSION OF DISEASE

Use of radionuclides in studying insect transmission of animal and plant diseases has already yielded valuable results; this is a most promising and fertile field of research. Epidemiological and transmission studies can be made with insect vectors labeled with radionuclides and with labeled viral, rickettsial, bacterial, protozoan, or nematode pathogens or parasites.

Studies of the epidemiological role of insects with radionuclide labeling during epidemic outbreaks have not been made, but several preliminary experiments of this type have been carried out. In a city in the Crimea, Shura-Bura (1952) studied houseflies in their relation to carrying diseases from outdoor privies. Human fecal material was saturated with a solution of phosphorus-32 containing 2 x 10^6 counts per minute per milliliter. Labeled flies were collected in traps in kitchens in two houses 20 to 30 meters from the outdoor privy. It was determined that flies kept in a laboratory after feeding on the feces remained labeled for 11 days. In Texas, Drosophila fruitflies were found to be labeled after visiting phosphorus-32 baits in privy pits, and labeled flies were recovered from eight of ten nearby houses (Pimentel and Fay, 1955). In other tests 4,000 phosphorus-32 labeled fruitflies were released in privy pits and were recovered in houses and other privies. Marked D. melanogaster were found up to 160 meters and D. repleta up to 320 meters from the release points. This indicated that a major portion of the fruitflies that were found in houses had at one time or another frequented privies. These results should be borne in mind in relation to outbreaks of dysentery and poliomyelitis.

The virus of yellow fever was transmitted by labeled Aedes aegypti by Bugher (1948). The virus content of labeled mosquitoes was the same as in the non-labeled. Various viruses have been labeled with phosphorus-32. Radionuclides have proved useful in studying the transmission of plant viruses by insect vectors. Polonium-212 was used by Hamilton (1935) as a tracer to show the quantity of material removed from a plant by a feeding aphid, Myzus persicae, and also the amount of ingested material that was returned to the plant during the next feeding period. Pineapple mealybugs Pseudococcus brevipes which transmit striping, spotting, and wilt disease of pineapple, fed on agar gel containing phosphorus-32 and became labeled and transferred phosphorus-32 to plain agar gels and to plants by their oral secretions (Carter, 1945). Tarnished plant bugs transmit a number of plant diseases. With phosphorus-32 as a tracer, it was found that when feeding the volume of oral secretion injected into the tissues of a host plant was from 0.05 to 0.25 lambda (Flemion et al., 1951, 1952). Many bacteria have been labeled with phosphorus-32. In an attempt to study the persistence and multiplication of Escherichia coli in the housefly, Jenkins (1954) fed flies phosphorus-32 labeled bacteria. The radioactivity and bacterial counts were determined daily and provided a quantitative method of determining the growth and persistence of bacteria in the fly. In other experiments *E. coli* was labeled with phosphorus-32 and fed to houseflies together with inert carmine. The time and amount of regurgitation and excretion of the bacteria was quantitatively checked by plating bacteria, counting the radioactivity and determining the presence of carmine. *Trypanosoma equiperdum* was labeled with phosphorus-32 by Moraczewski and Kelsey (1948). The filarial nematode *Wuchereria bancrofti* became labeled in the mosquito *Culex fatigans*, and the filarial *Setaria digitata* in *Armigeres obturbans* when these mosquitoes were treated in the larval stage with phosphorus-32. Use of strontium-89 proved to be toxic to *Culex* larva. The labeled mosquitoes fed on infected animals and the larval nematodes became labeled. This will be of value in studying the early development of the filarial infections in definitive hosts. (Dissanaike et al., 1957a, 1957b).

Use of radionuclides offers a technique for studying the dissemination, vector ability, feeding habits, and the numbers of organisms or size of infective dose of organisms introduced by medically important insects. To determine the size of a blood meal of oriental rat fleas *Xenopsylla cheopis*, hamsters were injected with phosphorus-32 with a dose of 179,250 counts per minute per milliliter. The volume of blood taken up by male and female fleas was accurately determined. (Jenkins, 1957) Shura-Bura and Kharamov (1961) used strontium-89 in rats and fleas.

An example is presented of the value of radionuclides in attempting control of Chagas disease, of which it is estimated there are about seven million human cases in Latin America. The major vectors are the triatomid bugs *Triatoma infestans* and *Rhodnius prolixus*. It appears plausible to control these vectors and the disease by using irradiation or chemosterilants and producing sterile males for self elimination the same as was done for the screw worm fly in southeastern United States. It is also necessary to determine the flight range, which would require a gamma emitter such as scandium-46 or iridium-192. Also joint use of an effective hymenopteran egg parasite *Telenomus fariae* should be used. Flight range studies of the parasite using the same radionuclide should be carried out. Population density studies using radionuclide techniques should be carried out with the triatomids and parasites. These studies are being initiated in Venezuela and appear promising.

POPULATION STUDIES

Efficient labeling and ease of detection by using radionuclides make possible more accurate studies on determination of the abundance and size of natural populations. This is done by releasing a known number of labeled insects in an area, collecting, trapping, and then calculating the ratio of labeled recaptures to labeled naturally occurring insects. By knowing the original number of released labeled insects and the daily mortality rate, the natural population can be calculated. Mortality rates can be determined during any stage of the life history, or at any specific time, using radionuclide labeling. Such labeling has a special value in evaluating effectiveness of control by chemical insecticides or biological methods. Longevity and mortality rates have been ascertained with radionuclides for certain insects reported in Tables 1 through 3. Population sizes of broods and generations emerging have also been determined for certain mosquitoes (Provost, 1952).

The use of insects for their own destruction requires that we know the total population and the population dynamics including reproduction, population increases, mortality rates during different stages and at different times, population size during hibernation and aestivation, and other important factors.

Radionuclide labeling offers an effective method of determining population density and dynamics. It is of importance in determining the effectiveness of any control operation, including insecticides, against a natural population.

Estimation of population size and population mortality during specific periods is possible using the radioactive tracer and release and recapture method. A total of 1,227 larvae of the moth *Panaxia dominula* were labeled by feeding on deadnettle *Lamium* that had been grown in water culture containing sulfur-35. The late larval and pupal mortality in colonies under natural conditions were estimated by the recapture method (Cook and Kettlewell, 1960). The total larval population was estimated on the basis of labeled larvae released, times the total adults caught, divided by the labeled adults caught. Of 4,038 adults sampled, 18 were labeled, which indicates the larval population to be from 198,185 to 225,210 with an adult population of 23,000. The late larval and pupal mortality was 88 to 90 per cent. In a second colony when 1,210 labeled larvae were released and the average number of adults was 77, the mortality was estimated at 94 per cent. The method shows that estimates can be made in wild populations using the radionuclide labeling technique.

Population estimates of mosquito larvae were made by using phosphorus-32 labeled and recaptured mosquito larvae in temporary and permanent pools by Welch (1960). When 4,300 labeled larvae were released in a permanent pool, recaptures indicated a recovery ratio of .2396 and an estimated population of 17,900 ± 1,423 (standard error) of the estimate. In a temporary pool, when 1,855 labeled larvae were released, the recovery ratio was .01585 and an estimated population of 117,000 ± 24,740 (standard error). It was determined that a large error is associated with a low recovery ratio. The technique and analysis are easy to use but it was indicated that large numbers of larvae should be labeled, that the experiment should be of short duration, and many samples taken.

The inherent difficulties of using this tracer and recapture method for a free-flying unenclosed adult population are illustrated in the following example. About three million phosphorus-32 labeled adults of the subarctic mosquito *Aedes communis* were released in a northern conifer forest at Churchill, Canada (Jenkins and Hassett, 1951). During the summer flying period of July 1 to August 15, a total of about 1,500,000 mosquitoes, mostly *Aedes communis*, were collected in a four square-mile area. Of these 141 were labeled, which is 0.0047 per cent of the released labeled mosquitoes, and about 0.01 per cent of the mosquito population sampled. Using the population density formula (total population equals the number of labeled adults released, times total number of adults caught, divided by the number of marked adults caught) this calculation is made as follows:

$$\frac{3 \text{ x } 10^6 \text{ x } 1.5 \text{ x } 10^6}{141} = 31.2 \text{ x } 10^9$$

This would be a total population density of 7.8 x 10^9 per square mile (12.2 x 10^6 per acre) or 30.15 x 10^8 per square kilometer (30.15 x 10^6 per hectare). Errors inherent in this population estimate include the following: (a) other species of biting mosquitoes moved into the forested area from the tundra including *Aedes impiger* (formerly *Aedes nearcticus*), and *Aedes hexodontus* which diluted the labeled and non-labeled Aedes communis population, (b) the non-biting habits of one of the races of labeled Aedes communis was not discovered until about half of the survey was completed, (c) the sex ratio of collected adults was not even, because of different habits of the sexes, and longer age of the females, and (d) inherent error in aliquot sampling to calculate populations. Nevertheless this estimate is probably the most reliable population estimate available for this species under arctic field conditions.

The place of radionuclides in entomological research has been well stated by Bruce-Chwatt (1956). "One should perhaps emphasize at the end of this review that it would be wrong to assume that the use of radioisotopes is a guarantee of miraculous discoveries. Radioisotopes are exquisitely sensitive and specific analytical tools but they are not more than tools and the results obtained depend entirely on the judicious approach to the whole research problem on which they will be used."

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UTILIZATION OF RADIOISOTOPES IN FORESTRY RESEARCH

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Forestry, like agriculture, is an old occupation. It dates back many thousands of years, but the use of radioisotopes extends only over a few decades. We are more accustomed to associate atomic energy with medical and military implications, or, more recently, with the production of electricity by atomic reactors. Nevertheless, radioisotopes have been used by biologists (5,44,45,86,87,88, 101,111, 157) and many industrial companies (10) to solve various problems, to make present techniques more efficient, and to aid in the development of new ones. The ever-increasing use is obvious when we realize that Canada shipped 79,000 Curies (Ci) in 1956 and over a million Ci in 1964.

The need for interdisciplinary cooperation is evident from the earliest days of radiobiology. A large proportion of today's research is under the direct aegis of atomic energy authorities to whom trees represent just another biotype, and it is up to the tree specialist to inform them of the special problems involved. Few may realize that the early work in the field of radiation-sensitivity in plants was done in collaboration with hospitals, which were using radium therapy. So it was with Weber (191) in 1922 who re-examined Molish's work of 1912-13 on the effect of x-rays on dormancy. While Molish used several tree species for his investigations, Weber used only lilac, (Syringa sp.) which was the only genus previously examined that was found to respond. He concentrated on this one genus to establish both maximum and minimum dosages and their various effects. It is interesting to note the four possibilities suggested by Weber:

1.-Activation or stimulation of enzymes.
2.-Change in permeability of plasmatic membranes.
3.-Rise in respiration intensity.
4.-Formation of wound hormones, which release the expansion of the meristem.

We do find that some of these theories, such as activation of enzymes by radiation, are still being postulated 40 years later, and still offer a wide scope for research.

The forester has many problems that are specific to the size and long life of the tree. For his investigations he has the choice of many isotopes, both radioactive (P-32) and non-radioactive (N-14) (37). Over one hundred radioisotopes can be produced in the reactor. The type of radiation emitted varies, but in our field we are interested especially in penetrating gamma rays (like x-rays) that will go through wood, soil and air, or the softer beta rays that are extremely useful in physiological and anatomical studies, although they

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travel but a short distance in woody tissue. Another characteristic property of great value is that of the half-life. Where the half-life of a radioisotope is three hours, after 30 hours (10 half-lives), the radiation will have decreased to an extent that a new experiment could be conducted again with the same material because the original radioactivity had become neglible (exceptions are rare cases where thousands of millicuries are used for initial work). Other radioisotopes offer a choice of gamma or beta radiation and longer half-lives (70).

We shall review here the applications of radioisotopes in several aspects of forestry. The scope is continually increasing and all instances can not be enumerated here. However, we hope it will demonstrate the versatility of these useful tools.

Forest Products

The most immediate influence on our lives is exerted by the finished products of the forest industry. Thus it might be appropriate to study first the contributions possible to this field. Because of the nature of our material and that of human endeavour, we should consider both laboratory application (159) and that supplied by accidental coincidence (atomic bombs and testing). Obviously in the latter case, when new properties are acquired, their effect might be of negative value and a "cure" has to be sought. One example of such damage was the acquisition of radioactivity by pulpwood through incorporation of fallout of radioactive products after the 1945 atomic tests (56,133). While the amount was probably insignificant by most standards, it was sufficient to affect the suitability of this pulp for photographic paper production and methods had to be devised to alleviate it.

Practical application has been made of soft beta radiation in the control of weight and moisture content in paper manufacture, (8, 9). The control instrument (Aquatel Betameter) consists of a beta source (Sr-90) on one side of the paper roll and a Geiger tube on the other. The penetration of the beta rays is proportional to the water content in the moving paper roll and the instrument gives its continuous percentage and serves as a guide (or automatic control) for the paper making machine. The density of wood of annual rings can also be measured with a finer modification of this instrument (136). Such procedure can save much time and energy in comprehensive studies related to tree breeding and wood dating.

Tracer experiments have found application in the studies associated with pulp production (43, 146, 150). The physical movement of wood chips, pulp fibres and pulping or bleaching liquors can be followed with radioactive isotopes. It is not necessary to use a tracer of the same chemical constitution as the material pursued. The use of short-lived isotopes will prevent a lasting contamination of the plant or product under investigation. The evaluation of stock blending at the "wet end" of a paper machine was facilitated with Ag I-131. The labelling was accomplished by soaking the fibres first in a solution of silver nitrate and then precipitating silver chloride within the fibre. The silver chloride was then converted into silver iodide (Ag I-131) by anion exchange with a solution of sodium iodide (Na I-131) (42). The turbulent flow in the headbox and drainage wire sections of two paper machines was compared in another investigation. I-131 labelling of fibres was not satisfacotry for the study of bleaching operations., because the iodine was removed during chlorination. A method using Ir-194 was developed in Finland. Wood chips have also been lablled with small pieces of Cu-64 wire or the addition to the stock of plastic chips labelled with La-140 oxide, so that flow characteristics of continuous kraft pulp digesters could be evaluated.

The penetration and distribution of preservatives is important in evaluation of different solutions and time of application. Radioactive isotopes, such as Cl-36 labelled pentachlorophenol have been used for such measurements in combination with infrared analysis (139).

Because chemical changes can be effected by radiation, research has been conducted on the exposure of wood to gamma irradiation from Co-60 to determine the effect of such irradiation on its chemical and structural properties (65), decay resistance (90, 155), and the grafting of styrene onto cellulose (81, 82, 142). The suggestion has been made that polymerization can be achieved by irradiation of monomers impregnated into wood and experiments in that direction have been carried out (143).

These examples are only a few of the possible uses of tracer techniques in forest products research and their practical application. Additional references are quoted in the excellent review of this subject by Clayton (42).

Tree Physiology

Tree physiology, because of the type of its problems, is the most obvious discipline where radioisotopes can be widely applied (61, 62, 77, 83, 93, 94). For example, in translocation studies dyes were formerly injected into the tree trunk and their movement could be detected only by cutting down the tree, or waiting for their appearance in the leaves. With a radioactive solution the sap movement can be followed without destroying the tree (51, 72, 119, 138, 175). Fifteen years ago Rb-86 was used as a tracer to study the movement in healthy and decadent yellow birch (Betula lutea Michx.f.) at the Petawawa Forest Experiment Station. Rb-86 has a gamma radiation which will penetrate wood and can therefore be detected with a probe (radioactivity detector) along the tree trunk. The specific half-life of 19 days permits its detection during the summer months when most of the studies are carried out. Yet within 10 half half-lives (6 months in this instance) another experiment can usually be repeated on the same tree. The different approach needed when working on living trees compared to the physicist's laboratory was realized when during initial experiments the Geiger tube was used for monitoring. During freezing weather the performance of this instrument was erratic until it was realized that the quenching agent within the tube condensed at low temperatures and the counting apparatus became unserviceable. Another drawback was the inability to obtain a uniform position for the probe during repeated observations on the same point. Accordingly a new portable scintillation counter, especially suitable for tree studies, was designed and constructed in cooperation with Atomic Energy of Canada Ltd. (63). It has a notch on the scintillation probe to fit over a permanent reference point on the tree. A further refinement with transistors and a mercury battery has resulted in a lighter instrument. In this particular experiment the Rb-86 moved up the trunk from the point of injection spiralling to the right - a reflection of the spiral grain of the wood within the yellow birch tree. However, in the tenth tree investigated, the radioisotope in the trunk spiralled to the left, indicating an opposite spiral grain to that in the previously studies trees. Klemm (93) at Tharandt, Germany, has used both the radioisotope (P-32) and thermoelectric techniques to follow the transpiration stream and found a good correlation between the two methods. He contrasted the left spiralling in birch (Betula verrucosa Ehrh.) with the right spiralling in poplar (Populus "Oxford"). A comparison in Russia (185) between the dye and radioisotope techniques in birch and spruce showed a difference of 50 per cent between the rates of the two indicators (higher for the radioisotope). While weather, particularly humidity and temperature, was a deciding factor in the rate of movement (2), a difference between conifers (spruce) and hardwoods (poplar, birch, oak) was evident. This difference favoured the hardwoods while in leaf. A similar response was observed in the United States (99) and Canada (59). Recently Woods and McCormack (199) developed two more scintillation probes for tree studies.

The path of movement of the radioisotope within a tree may be ascertained from samples removed with an increment borer. The various parts of each sample may be checked for radioactivity either in laboratory counters or by using the authoradiographic technique (24, 36, 132, 181) whereby a photographic film is placed over the increment (or around the trunk in large trees). Film exposure is effected by the penetrating radiation. This technique can also be used for mapping of radioisotopes within a leaf. In such an experiment, Ca-45 was concentrated along the central part of the blade and radiated outwards along the veinlets (60). Zimmerman (207) has reviewed translocation work in phloem.

A variation in the character of the translocation stream between two species of oaks was demonstrated by Kuntz and Riker (99) in Wisconsin, U.S.A., with Rb-86 and I-131. The diffuse movement of radioisotopes throughout the trunk and crown of the northern pin oak (*Quercus ellipsoidalis* E. J. Hill) was in contrast to the linear flow in the trunk and certain branches of the bur oak (*Quercus macrocarpa* Michx.). The bur oak functioned like the yellow birch and white pine (*Pinus strobus* L.) at Petawawa. The rate of water transport (Na-24) in forest trees was studies in Sweden (103) in conjunction with the thermoelectric method. This latter technique gave slightly lower values.

Experiments can also be conducted to determine if the translocation stream is unidirectional at any given time (174, 187). Research undertaken in the United States indicated simultaneous movement of P-32 and C-14 in opposite directions in the phloem tissue of willow (*Salix* sp.) (41). Independent transport of individual elements was also confirmed when tritiated water with dissolved P-32 was introduced directly into the leaves (21).

The problem of destroying experimental leaf material by sampling during the study, which results in approximation rather than duplication of such sampling, can now be alleviated thanks to modifications of the already described Aquatel Betameter. These modified instruments may be used to measure leaf moisture (126) or leaf thickness (204).

There are several questions and precautions that have to be considered before introducing herbicides into a plant community. They have to be effective against the intruders but harmless to the crop plant and non-toxic to the animals that eat the exposed vegetation. The effectiveness against any given species will be influenced by the time of application as well as the sensitivity of individual organs. Labelling of herbicides with radioactive isotopes (18, 29) will facilitate the perception of the path of translocation and metabolism after any given application. Although this method has been widely used in agriculture (106), its potential in forestry has not yet been fully explored. One instance of such use is that by Volger (189) in bracken (*Pteridium aquilinum* (L.) Kuhn) at Hanoversch-Münden, German.

In photosynthesis some early applications of radioisotopes were made before 1939, but the main contributions date from 1946 onwards. At that time, Calvin's group (17, 39) in California concentrated on the path of carbon in the process and they and other workers (3, 141) have greatly advanced our understanding of this vital process. It is a bit frustrating for a forester to realize that the bulk of such exciting research has been conducted with unicellular green algae. It can be only assumed that some of the basic facts discovered with these small, easily controlled organisms, can be utilized in forestry investigations. The effect of gamma irradiation on photosynthesis in trees was reported by Bourdeau and Woodwell (30).

Work both in Germany (130) and the United States (30) has shown that photosynthesis occurs at a reduced rate in coniferous needles in winter. In addition, the use of C-14 in forest trees has provided information on the assimilation of carbon dioxide (100, 127) and the translocation and incorporation of newly formed compounds in new tissues. Experiments with C-14 labelled sodium acetate fed through cut branches of Monterey pine (*Pinus radiata* D. Don.) have shown that acetate is incorporated into the terpenes. Durzan and Steward (50) used C-14 to study nitrogen metabolism in white spruce (*Picea glauca* (Moench) Voss).

It has been known for over a century that application of mineral nutrients to leaves and stems has sometimes a beneficial effect on growth (196). Yet interest in this approach has intensified over the last thirty years. The use of radioisotopes has shown foliar absorption of materials such as orthophosphoric acid, potassium carbonate, and urea, even in midwinter (195). Foliar and bark applications may have more immediate effect than the application of the same nutrient to the soil (95). It may be more efficient not only because it is supplied closer to the seat of utilization, but also because it avoids the tie-up of the nutrients into insoluble compounds in the soil, or the interference of micro-organisms. Such direct application can therefore be used for rapid correction of mineral deficiencies, and provide specific nutrients at critical periods, adjust nutrient levels to climatic variations and aid in recovery from winter injury (183).

For maximum efficiency of spray applications, an addition of a wetting agent is often desirable, for it will result in a uniform film of liquid over the plant surface. A more even absorption of the nutrients is thus effected while the danger of leaf burning is minimized. It should be realized that these agents are not universal in their reactions and they have to be chosen with a consideration both towards the spray and plant contemplated (85). The importance of proper balance between the offered elements can also be checked with the radioisotope technique. When boron was included in a spray the uptake of P-32 in the solution was reduced, but that of C-14 labelled sucrose was increased (128).

While we can use the property of permeable leaf membranes to gain a speedy entrance for desirable solutions, it should be remembered that nutrients can be also leached out of the leaves during a heavy rainfall. Their path can again be followed with radioactive labelling of critical elements. Thus Swanson (178) considers the indicated mobility of Ca-45 in western white pine (Pinus monticola Dougl.) reported by Ferrell and Johnson (58) to be only apparent, a result of re-entry from the soil of Ca-45 which has been leached out of the leaves by rain.

The competition for minerals between individual organs of a plant has been known to exist for a long time and is used in identifying some of the deficiencies in plants (6). Yet the extent of this competition in the total plant could not be determined without radioactive isotope application, except in seedling material. That is particularly true for the competition between the roots and the aerial parts. Biddulph (21) investigated this aspect of retention and transport by the root for both P-32 and Rb-86 over a 24-hour period and found that diurnal variations in both retention and translocation were evident. Kramer (96) used P-32 to study the effects of respiration inhibitors on the accumulation of P-32 by roots of loblolly pine (Pinus taeda L.). He noted that the meristematic region of the loblolly pine root accumulates large amounts of P-32, but very little moves out of the root tip. Heavy uptake occurs in the root hair zone and through the epidermal cells behind the root tip (97). Both Ca-45 and S-35 have been used in the study of root hairs and their function (110).

Minor elements are difficult to assess in their importance to the proper development of a tree. Their detection and abundance in individual localities can well be studied with the aid of activation analysis (33, 114). This is a method of measuring concentrations of certain elements in a given sample by observing the characteristic radiations emitted by the radioisotopes produced by selected nuclear transformations (113). The selection of this technique to assist in chemical analysis may be decided by its sensitivity and speed. Although its application may involve two approaches, the absolute assay and the comparative assay techniques, the latter, which uses standard samples, is in more general use since it requires relative measurements only and is more convenient.

Forest Ecology

While some aspects of this field are closely related to tree physiology and the designation of physiological ecology would be more appropriate, the properties and influence of the underlying soil are hard to dissociate from the overall effect. Basic information for silvicultural purposes is again provided by the multifold applications of radioisotopes (156). That this information might be more than of academic interest is indicated by the attention it receives at such an establishment as that of the Weyerhaeuser Co. (7) in the United States. There the distribution of roots from an individual tree is being mapped through tracer techniques (Rb-86) and the uptake of nutrients followed with the labelling of the translocation stream. Similar work was done on coffee roots in Costa Rica (149) and in fir roots in Germany (206). In both instances, the shallow roots were the most efficient absorbers. Woods et al. (198) in their search for methods to pursue various elements through the ecosystem, have treated soil with methyl bromide to increase the uptake of I-131 by pine seedlings.

Mineral cycle studies lend themselves to tracer methodology (46, 193). We think first of Tamm's work (179) in Sweden with the leaching of minerals from leaves by rain and these studies have been extended by the use of radioisotopes (184). Auerbach and Schultz (16) at Oak Ridge have an active program in this field related to ecological changes following major mineral modifications. In the transformation of organic matter in the soil in relation to the availability of nutrients to plants, more work has been conducted in the field of agriculture (114) than forestry (125, 180), yet there is much to be learned from this former work as reported at the IAEA (International Atomic Energy Agency) symposium on radioisotopes in soil-plant nutrition studies in 1962 (12).

The availability of individual elements to plants does not depend only on their presence in the soil, but particularly on the form in which they are represented. The usefulness then depends further on the plant which utilizes it, for not all plants have the same assimilation potentialities. Thus it has been long estiblished that while only a limited number of plants can be the primary recipients of selenium from the soil, when these plants decay the selenium in a different form becomes available to crop plants, which in turn, become toxic to man and beast (92). In more recent times the localization of Sr-90 in the leaves of potatoes after radioactive fallout would appear encouraging, until it is discovered that through leaf decay this Sr-90 becomes available to the next crop, is absorbed by roots and concentrated in the tuber (112).

The use of C-14 O_2 has been mentioned in photosynthesis studies and it may also be utilized through dilution techniques for movement and concentration of carbon dioxide in forest investigations and in meteorology (49). Labelling of fluids using radioactive isotopes is useful when we are especially interested in the rate and flow of air. The flow is dependent on many variables including temperature, pressure (wind), and geometry (i.e. shape of the surfaces in contact with the air). Three methods include dilution, continuous sample and total count. They involve the injection of a tracer at one point and subsequent measurement at another point sufficiently far away to allow for complete mixing. Errors result from incomplete mixing. If the measuring point is too distant the tracer is overdiluted. For gases the tracer must not be poisonous, must be available and stable in a gaseous form, and must not be too heavy to interfere with complete mixing. Activated argon has been useful in this field. Boron may be used for the application of activation analysis in gaseous studies.

Substances excreted by plants through their root systems may inhibit growth of the same or different species on replanting. This effect is recognized in orchard trees, but little is known of the substances involved. At the East Malling tree physiology colloquium in 1964, Crafts suggested that whole trees be exposed to a C-14 carbon dioxide containing atmosphere and their exudates studies over a long period.

The soil biosphere includes many different organisms that vary in their tolerance to radiation. Thus investigations in progress at the British Atomic Energy Establishment at Wantage show promise of using this radiation sensitivity to understand (and control) such processes as carried out by nitrogen fixing organisms (31, 32, 34).

Root grafts have been recognized for many years (153), but it is only within the last 15 years through the use of radioisotopes that their abundance and probable implications have been investigated. Using these techniques, Yli-Vaakuri (205) in Finland and Bormann (26, 27) and others (122, 197) in the United States, have contributed towards our understanding of the significance of roots grafts in plantations (living stumps) and the interrelation of dominant and suppressed trees in the rhizosphere (28).

The groups at Brookhaven (162, 163, 164, 166, 167) and Savannah River (71) have been concerned with an overall reaction of the biosphere to different types of radiation (waste, fallout, single source) (11). References to trees form only a small part of this wide ranged program. The ecological research group under Auerbach (15) at Oak Ridge, has made extensive studies on the environmental radioactivity in the White Oak Lake Bed. This lake bed, which was drained in 1955, is part of the waste disposal system, and information was required on the movement of fission products (48). The study followed plant and insect succession on this drained lake bed and their concentration of Sr-90, Cs-137, and Co-60. It becomes interesting to us after 1959, when an increase of trees, particularly willows, becomes evident at the expense of herbaceous vegetation. The most abundant new trees in addition to the willow include sycamore (Platanus occidentalis L.), smooth sumac (Rhus glabra L.) and green ash (Fraxinus pennsylvanica var. subintegerrima Fern.). Within this group, Rhus (Sumac) seems to be most effective in concentrating Sr-90, while Cs-137 and Co-60 concentrations are much the same between the four genera.

Forest Soils

The practical use of isotopes has perhaps been most readily accepted and received the greatest scope of applicability in fertilizer research (12, 104). The efficiency of a fertilizer in maintaining a seedling and a mature tree healthy is determined by many factors such as the soil type, the chemical form of the fertilizer, the presence of other nutrients, the climatological conditions and the growth stages of the tree. Much of the initial work has been done with P-32 where insolubility (177) and fixation of phosphates distribution of the element in the root zone and its upkeep in available form (192). The efficiency of a particular fertilizer to trees under a given set of environmental conditions (160) can be determined by using labelled compounds and measuring the activity both in the soil solution and in the tree (4, 14). Thus for a particular soil the concept of "A" value was first developed by Fried and Dean (66) in 1952 and later it was found that some of the variables encountered could be eliminated by placing the tagged phosphorus fertilizer in concentric bands around the seed (145). Such practice assured an even distribution for the developing rhizosphere while minimizing the contact and hence interaction between the soil and the fertilizer for the "A" value (lb P/acre of equal availability to that of fertilizer standard = $\frac{\text{Plant P derived from the soil}}{\text{Plant P derived from the fertilizer.}}$)

The efficacy of seed pelleting can also be explored to ascertain the actual distribution of the fertilizer and rodent repellant in the immediate environment of the dispersed seed.

Water content of the soil is of especial importance in tree growth, yet quantitative studies of its seasonal and annual variations have been both time consuming and difficult. Methods of measuring water content include gravimetric, electrometric and radioactive techniques (13, 78, 79, 172). The latter techniques utilizes the principle that neutrons are scattered by an atomic nucleus and the lighter the nucleus the greater the loss of energy. Thus the more hydrogen or water the matter contains, the more rapidly do fast neutrons lose their energy in it, and are reduced to the thermal level of the environment. In other words, the greater the water content of the soil in which a fast-neutron source is embedded the more thermal neutrons will be found. Spinks (171) in Canada, and others (67) have shown the close agreement between the standard gravimetric and neutron techniques. Van Bavel *et al*. (186) have shown that this type of moisture determination is almost independent of the type of soil, though this has been questioned by soil scientists who believe in calibration of each soil type. Davidson *et al*. (47) have also shown a temperature effect. The advantage of the neutron probe is that it provides immediate information on the spot where the investigation is conducted.

Movement of water within the soil has been followed with radioisotopes (H-3) (13, 80, 89, 200), though the ion exchange properties of the soil may complicate such a study. Tritium absorbed from the soil is incorporated in the current annual ring and offers another technique of following water movement (38). This isotope was used by Lewis and Burgy (107) to study the relationship between ground water and roots of oak. Sand and silt movements under water were also studied by Putnam and Smith (140).

Tree Breeding

A successful breeding program depends on the availability of many characteristics and their advantageous recombination, or the selection and proliferation of individual bud sports (22, 165), the result of a single mutation. New gene combinations can also be obtained through mutations. Spontaneous or natural mutants arise very infrequently, something of the order of one per million. Radiation increases this frequency many hundred-fold and might also favour a rearrangement of genes through breakage and resulting crossing-over in chromosomes. Yet let us not assume that the production of mutants will solve all the breeding problems, for mutations, whether spontaneous or induced, are usually detrimental, and we have to be therefore prepared to work with great numbers. Also the radiation dosages which maximate mutation frequencies kill about half of the exposed individuals. This critical level is called lethal dose 50 per cent (LD-50) (35). The dormant seed, because of its inactivity and small size, has many advantages as an experimental object over the growing tree

Although the classical work on radiation-induced mutations was done forty years ago by Muller (124) on the fruit fly *Drosophila*, it was Gustafsson (75) and his colleagues (53) in Sweden who, besides cereal research, have recognized the potential of radiation genetics in forestry. It is the ionizing radiation that is absorbed by the tissue rather than that which passes directly through the material that causes most of the biological changes, and is of potential use in tree breeding. Electromagnetic radiation, such as X and gamma radiation (54) and particulate radiation, such as alpha and beta particles (52), protons and neutrons, produce ionizations when they pass through material. Alpha, beta and gamma radiations are emitted by radioactive isotopes and induce effects similar to x-rays. Alpha and beta radiation have limited usefulness as an external source, because of their low penetration, but could cause mutations if they were introduced directly into the tree. Both the highly energetic or fast neutrons and low-energy slow or thermal neutrons have been used in mutation experiments. Thermal neutrons are effective in producing mutations in both seeds and scions. Thus when mutation experiments are considered, it is necessary to know the tissue-penetration capacity of the different types of radiation. If the radiation dose is low, there may be no immediate apparent effect, but with a higher dose the effects will include: a) death, b) reduced growth or germination, c) morphological abnormalities, and d) genetic effects (76, 102, 151, 152, 161). In additions there may be a stimulating effect on growth at certain levels of radiation (123, 182), but there is much work still to be done in this field to evaluate this particular effect. Radiosensitivity varies widely among organisms and has been shown by Sparrow and Woodwell (169) to be related to nuclear volume, chromosome size and number. The effect of low level chronic gamma irradiation on sexual reproduction of forest trees was studies by Mergan and Stairs (120, 121).

At first glance at the extensive work by Sparrow and his colleagues (168, 170), the most striking result for a forester is the correlation of mean energy absorbed at lethal exposure per chromosome, where regardless of degree of ploidy, the lethal dose was always lower for woody species, particularly conifers, compared with herbaceous plants. They consider the interphase chromosome volume to be the determinant of radiosensitivity. The chromosome number assists in the estimation of average volume of the chromosome (by dividing the volume of the interphase nucleus by the number of chromosomes in it). The difference between the tolerance of herbaceous and woody species exposed to chronic irradiation was about ninefold. This difference in sensitivity was also noted independently by Platt (135).

Woodwell and Sparrow (202, 203) have compared shoot growth and tree mortality in a number of woody species which were subjected to chronic gamma radiation from a Cs-137 source. The responses were predicted according to the nuclear volume and chromosome numbers of the different species. Observed growth was generally less than predicted. Two factors were considered responsible for this variation: the higher physiological stresses in the field and the fact that woody species appear more sensitive to ionizing radiation than herbaceous ones of similar chromosome number and nuclear volume. Okunewick et al. (129) explored the effect of a single dose of acute gamma irradiation on young pine shoots while Woodwell and Miller (201) examined radial increment after chronic irradiation.

Polykov and Dmitrieva (137) in the USSR have used S-35 and P-32 labelled pollen to investigate the existence of multiplicity of fertilization and believe that more than one pollen grain contributes to the metabolites of the developing seed. The path of Cs-137 has been followed through the tree, into the floral parts, seeds and resulting seedlings by Witherspoon and Brown (194). Information on the distribution of pollen is necessary both in studies of gene exchange between partly isolated populations and the assessment of fertilization conditions in forest stands and plantations. Pollen from a specific tree can be labelled with a radioactive isotope (73), but this procedure may not be possible in populated areas. Hence the use of the indicator activation technique as developed by Glubrecht (69) in Germany is appropriate. Manganese was found to be suitable in this work for it is not toxic when injected into trees where it is translocated into developing pollen grains, and it may be readily activated later in a reactor. Although natural manganese content of certain trees must be considered, this approach offers interesting possibilities.

In cytological studies only low-energy beta emitters such as P-32, S-35, C-14 and especially H-3 are useful. Utilization of both H-3 and C-14 thymidine provides an elegant double labelling method for intracellular investigations through microauthoradiography.

Seed quality can be assessed through radiography (109, 154). Thus the investigator can determine the condition of the embryo, endosperm and seed coat, and ascertain physical reasons for poor germination without tedious time-consuming micro-dissection. Another technique for the non-destructive study of seed is that of electron spin reasonance (19, 20). Seed dispersal has been studies in Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) with radioisotopes (105).

Forest Entomology and Pathology

It is an accepted fact that an accurate insect control plan is essential for a production of unblemished fruit, such as apples, pears, and peaches. Although the losses to forest trees are characterized by periodic outbreaks rather than a continuous threat, because of the long-term nature of forest crops, the damage might be just as disastrous and expensive. While, until now, more research has been done on orchard than forest insects, and while both are concerned with injury to trees, we shall embrace both in our discussions. The use of radioisotopes (84, 108) under these circumstances can be threefold: (a) in establishing the life history and behaviour of the insect, (b) the path taken by the applied insecticides, and finally (c) the use of the radioisotope to effect the control directly.

(a) An exact knowledge of a life cycle (91, 176) is essential for designation of effective controls; this can become extremely difficult with forest insects, where a part of this cycle is often spent underground or under the bark, in the buds or wood of a tree. Tagging with radioactive tracers or the use of indicator-activation techniques (147) will not only facilitate the following of these stages (23), but also the establishment of a pattern of distribution of the flying adults.

(b) The path and disintegration steps of insecticides, fungicides and herbicides (64, 190) may form a deciding factor in their choice. This pertains not only to agricultural crops, with the immediate threat to the human consumer, but also to the control of forest insects which form an important link in the wildlife food chain, i.e. effect of budworm spray on trout population, concentration of the insecticides in woodcocks (hunted by people), etc. (68, 134).

(c) The sterile-male technique, which involves the release of large numbers of male insects sterilized by radiation (173). Their mating will produce non-viable eggs, and hence reduce natural populations of epidemic proportion.

The tracers successfully used include, P-32, S-35, Ca-45, Sr-89, Co-60, Zn-65 and I-131. They have been either directly introduced into the insects by contamination of their food or water (40), or by injecting radioisotopes into animal - or plant - hosts. They may also be connected to them by purely mechanical means such as the insertion of radioactive wire into the body of a pupa or the dipping, painting, spraying of insects by radioactive solution, or attachment or clipping on of the radioactive source.

The effect of disease organisms on growth of forest trees offers a wide scope for the application of tracer techniques. Kuntz and Riker (99) of Wisconsin used radioisotopes in their classic investigation of the oak wilt fungus and showed that both anatomical characteristics of the species and natural root grafts were important in the spread of the disease within trees and from one tree to another. Similar work in Canada demonstrated a reduced rate of the translocation stream movement in decadent yellow birch (63).

Besides direct application in determining the path of the pathogen, radioisotopes can also be effective in establishing the extent of damage in the tree. Eslyn (57) and Ely and Loos (55) used gamma radiation for radioautography of trees suspected to trunk rot and have detected cavities and decay in trees up to 56 cm in diameter. In 1961, Parrish (131) reviewed the more than

20 years of progress in such log-examination and from his own experiments with several sources (particularly Cs-137, Sm-144 + n and Sn-133) he concluded that radiation energy of 23 Kev was most effective for low density woods, while 135 Kev were needed for those of high density. Similarly Křistek (98) in his Diprion study used this method to determine whether the pupal cases were normal, parasitized by fungus, or empty.

The role of mycorrhizae in the nutrition of a tree has been long disputed. Because of the nature of the relationship between the tree, the fungus and the soil, approximations concerning this role could only be suggested until Melin and Nilsson (115, 116, 117) in Sweden introduced the radioisotopic approach to the problem. By feeding the mycorrhizae with the labelled nutrients (e.g. N-15, P-32, Ca-45, C-14) independently from those available to the tree roots, they were able to follow their path into the tree and the proportion of nutrients per plant thus acquired. They also exposed the needles of aseptically grown Scots pine (Pinus sylvestris L.) seedlings to C-14 labelled carbon dioxide and recorded a quick transport of photosynthates into the fungal mantle which contained a higher amount of the labelled C-14 than the uninfected roots (118). Ritter and Lyr (148) in Germany have used P-32 to determine the effect of mycorrhizae on the utilization of phosphate from different sources. Slankis et al. (158) in Canada observed that after supplying white pine seedlings for eight days with C-14 carbon dioxide, the roots liberated a complex mixture of more than 35 organic compounds into the rhizosphere. This agrees with work by Akhromeiko and Shestakova (1) and suggests the effect of trees on both the microbiota and regeneration (74, 188).

In conclusion we should like to emphasize the necessity for cooperation between foresters and radiobiologists - many problems require the coordination of various disciplines and the results of symbiosis will be especially rewarding in the application of radioisotope techniques to forestry research. Not only will forestry be advanced, but the forester himself can provide much valuable information from his experiences that will be of great help to those in atomic research, especially in the field of radioactive waste disposal. We wish sincerely to allay the suspicions and fears of those of you who feel that there is a special danger involved in work with radioisotopes. The safeguards established by your respective atomic energy authorities and the high degree of sensitivity of measuring equipment make the peaceful application of radioisotopes as safe as ordinary chemical procedures. If you feel that a large investment in monitoring equipment is prohibitive, this may be often avoided by the use of authoradiographic techniques, or, as we have suggested, by working in collaboration with radiobiologists - you will find that they are usually only too willing to share their knowledge and monitoring equipment to assist in the promotion of forestry research.

There are courses available in many countries in the use of radioisotopes in biological research and last year the FAO/IAEA Division of Atomic Energy in Agriculture sponsored the first International Course on the Use of Radioisotopes and Radiation in Forestry Research. This was held at the Institute of Radiobiology in Hanover, Germany. Undoubtedly more courses of this nature will be given as the demand requires.

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Use of Radioisotopes in Hydrobiology and Fish Culture

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ABSTRACT

Use of radioisotopes has increased rapidly in hydrobiology and fish culture. Their use, especially P^{32}, to study circulation of nutrients has been demonstrated and offers opportunities in problems of lake metabolism. The most extensive use of isotopes has been to determine photosynthetic activity in plankton through C^{14} uptake. Applications and limitations are discussed. Isotopes have been successfully used in food studies of fish to determine food selection, metabolism, and storage. Water movements in fresh and salt water and in sewage problems have been successfully followed by use of various isotopes. Marking of aquatic animals with radioisotopes has many possible applications, but has been little used because of some inherent problems related to danger to organisms and in field use. Extent of future use of isotopes in hydrobiology will be determined by further study of hazards and public acceptance of field studies.

Many useful applications of radioisotopes have been made during the past decade in medicine, industry, and in basic science. This report reviews recent research in hydrobiology and fish culture in which radioisotopes have been used. The growing list of subjects that have been investigated with radioactive tracers has led the authors to feel that such a report is timely. It has been prepared to acquaint fishery workers with new research possibilities that have arisen as radioactive materials have become available.

No attempt will be made to summarize the rather extensive literature dealing with the biological effects of fallout and radioactive wastes released into rivers at reactor sites. Many of these studies have provided useful ecological data, but they have been primarily concerned with the evaluation of hazards rather than with exploring new avenues of scientific interest. Readers are referred to a recent bibliography compiled by Klement and Wallen (1960) for references in this field.

Isotopes have been employed in almost every field of biological research. Within the fields of hydrobiology and fish culture the principal areas of research in which isotopes have been used are: (1) chemical cycles in lakes and ponds; (2) productivity measurements; (3) food relationships; (4) fish diseases and fish nutrition; (5) tracing movements of water, pollutants, and sediments; and (6) marking aquatic animals.

Several other review articles dealing with the use of isotopes have proven helpful in the preparation of the present report. Of particular interest is the paper of Zhadin, Kuznetsov, and Timofeev-Resovsky (1958) which summarizes in considerable detail hydrobiological studies which have used isotopes in the U.S.S.R. and the lectures given at the symposium on *Marine Biological Applications of Radio-Isotope Research Techniques* in Naples during September 1957. These lectures have been published as a supplement to volume 31 of the Publications of the Zoological Station of Naples. The reviews of Griffin (1952) and Pendleton (1956) summarize earlier studies, particularly those concerned with marking animals with isotopes.

CHEMICAL CYCLES IN LAKES AND PONDS

Significant contributions to the understanding of the biological pathways nutrients and chemicals take in lakes and ponds have been made by adding radioactive tracers to the water. Radioactive phosphorus (P^{32}) has been most widely used, because its short half-life makes it relatively safe in field experiments and because it is a nutrient element which is taken up rapidly by bacteria and plants and soon appears in almost every form of life. Readers are referred to a recent and excellent review of this subject by Foster (1959).

With P^{32} Hutchinson and Bowen (1950) demonstrated that phosphorus was continually passing from the epilimnion to the hypolimnion of stratified lakes through the sedimentation of seston. Two treatments of Nova Scotian lakes with P^{32} by Hayes and coworkers (Coffin, Hayes, Jodrey, and White-

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[1] Cortland, New York.
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way, 1949; Hayes, McCarter, Cameron, and Livingstone, 1952; Hayes and Phillips, 1958) led to some interesting observations on the movement of phosphorus in lakes. These authors showed that phosphorus atoms are continually and rapidly exchanged between the lake water and other forms of solids in the lake system (*e.g.*, mud, plankton, bacteria, rooted plants). The disappearance of P^{32} from the water of a lake was found to be similar to the disappearance of P^{32} and other tracers in biological systems studied in the laboratory. From data on the rate of disappearance, calculations can be made of the turnover time, which is the time it takes phosphorus atoms to move through the "solids" of the lake and reappear in the lake water. Hayes *et al.* (1952) also recognized the similarity between the manner in which P^{32} disappears from lake water and the manner in which natural phosphorus is lost from water after a lake or pond is fertilized with inorganic phosphorus. Phosphorus added as a fertilizer appears to act like P^{32} and must equilibrate with phosphorus in the "solids." Soon after fertilizer is added, therefore, the phosphorus content of the water falls to a level only slightly higher than before fertilization.

A similar study with P^{32} by Rigler (1956) in Toussaint Lake in Ontario verified many of the findings in the Nova Scotian waters and also emphasized the importance of planktonic bacteria in the turnover of phosphate. Recently Pomeroy (1960) published the turnover rates of dissolved phosphorus in a variety of natural waters. These figures suggest that short residence times of phosphorus are indicative of depleted phosphate and/or high metabolic activity. Zhadin, Kuznetsov, and Timofeev-Resovsky (1958) report studies in the U.S.S.R. in which P^{32} and Ca^{45} have been used in experiments on the fertilization of fish ponds. The experiments have demonstrated advantages in using a combined mineral fertilizer rather than one containing only phosphorus.

With P^{32} Rice (1953) studied the exchange of phosphorus between cells of the diatom *Nitzschia* and the medium. He found that in time diatom cells will convert some of the exchangeable phosphorus into organic compounds in which it is nonexchangeable.

Zicker, Berger, and Hasler (1956) were able to determine the depth from which phosphorus can be released into the water from lake bottom soils by using P^{32}. They found that virtually no phosphorus was released without stirring or agitation from a depth greater than one-quarter inch below the mud surface.

Much less use has been made of elements other than phosphorus in studying movement of materials in lakes. Likens and Hasler (1960) added radioactive sodium (Na^{24}) to the bottom water of a small meromictic lake and studied its horizontal and vertical movement. Using radioactive sulphur (S^{35}) Sugawara, Koyama, and Noda (1954) obtained evidence that ferric hydroxide flock sorbes sulphate ion and carries it to the lake bottom. Zhadin, Kuznetsov, and Timofeev-Resovsky (1958) reviewed the studies of Ivanov who used isotopes to study the processes of sulphate reduction and sulphide oxidation in lakes. He found that sulphate reduction occurs chiefly in the surface layers of bottom deposits and that the surface layer of Solyonoye Lake produces H_2S at the rate of 20 milligrams per liter per day.

The foregoing studies are examples of how radioisotopes may be used to learn more about the chemical cycles of natural waters. Possible applications of isotopes in studies of this type are far from being exhausted. Many interesting problems suggest themselves. Radioactive iron (Fe^{59}) with a half-life of 45 days could be used to investigate the iron cycle and some of the complex relationships between iron and the organic substances of lake water. Radioactive cobalt (Co^{58}), which has a half-life of 72 days, might be used to study vitamin B_{12} and its translocation in aquatic habitats. The possibility of labeling organic compounds should not be overlooked. Many of the herbicides and pesticides which now find their way into natural waters can be labeled and in this way traced through the food chain. Thus we have at hand a means of investigating the effects of these substances upon aquatic life with more precision than hitherto possible.

PRODUCTIVITY MEASUREMENTS

The isotope most widely used at the present time in hydrobiological studies is $carbon^{14}$. Its principal use is to measure the uptake and fixation of carbon by phytoplankton. From such measurements it is possible to calculate an estimate of the rate at which the phytoplankton in the ocean, a lake, or a pond is producing organic matter.

Technique

The techniques used by various investigators have differed in details, some of which may be unimportant. Recent studies, however, have indicated that certain seemingly minor differences in technique lead to sizeable differences in results. Perhaps the most useful reference on technique and one which includes a discussion of reliability and inherent errors, is the paper by Doty and Oguri (1958).

Water samples are collected from the sea or lake surface or at any depth at which photosynthesis measurements are desired. In lake studies ordinarily enough depths are sampled to give a profile through the photosynthetic zone (surface to a depth at which less than 1 percent of surface light remains). The type of sampling bottle used seems to influence the photosynthetic rates that are obtained in marine studies (Doty and Oguri, 1958). Three clear-glass, pyrex bottles of 250-milliliter capacity are filled from samples collected at each depth. Two of the bottles are used as "light" bottles and the third serves as a "dark" bottle. The dark bottle is either wrapped with heavy aluminum foil or covered with opaque tape or black paint to exclude light. One ampoule of radioactive carbonate solution of known activity is introduced into each bottle. The ampoule is then rinsed and the rinse water is added to the bottle. In lake studies the bottles are incubated in the lake at the depth at which they were collected. In oceanographic studies samples are sometimes incubated in a box under controlled light conditions and at sea surface temperature (Doty and Oguri, 1958). The incubation period usually used is between 2 and 8 hours. After incubation, samples are removed from the lake or incubator and filtered through a Millipore filter disc of HA porosity. The filter disc is washed with 20 milliliters 0.001 N HCl, removed from the filter holder, and stored for counting. Since the isotope has a long half-life, counting can be delayed indefinitely. The foregoing part of the procedure can be carried out in the field by trained technicians. Once a reliable procedure has been established, field work does not presuppose any expert knowledge.

Counting and calculations of carbon fixation rates can be carried out by the investigator if equipment is available, or planchets can be mailed to the Central Agency for C^{14} determination at Charlottenlund Slot, Denmark, for counting and calculations (see below). A windowless gas-flow type counter is preferred for counting but a thin window Geiger-Müller counter can be used. Samples are usually counted for from 3 to 10 minutes, depending upon their activity. If a calculator is used, an operator can complete all the necessary calculations while samples are being counted.

Materials

The ampoules containing radioactive sodium carbonate solution must be carefully prepared. Their activity must be accurately known. Ordinarily they are made up so as to contain between 2 and 4 microcuries of C^{14}. Ampoules may be prepared from solid barium carbonate purchased from the Oak Ridge National Laboratory or from a number of concerns handling radioactive chemicals. Several companies will on order furnish ampoules containing the desired activity.

In 1958 UNESCO funds were provided for the establishment of a central agency for C^{14} determinations at Charlottenlund Slot, Denmark.[3] This agency was organized to provide standardized C^{14} ampoules, to count C^{14} samples, and to calculate carbon assimilation rates. It operates on a nonprofit basis and its services are available to all scientific organizations in the world. An organization can purchase either the standard ampoules alone or at a slightly higher cost can secure the counting and calculation services (numbered membrane filters are furnished as a part of the counting services). Water sampling and filtering equipment can also be purchased from this agency.

Applications

Widespread use of this technique in oceanographic studies (Steemann Nielsen, 1952; Doty and Oguri, 1957; Ryther and Yentsch, 1958) has been followed by somewhat more limited use in fresh water (Nygaard, 1955; Frey and Stahl, 1958; Rhode, Vollenweider, and Nauwerck, 1960). Although the method measures photosynthetic processes within the confines of a bottle and therefore is only an approximation of this phenomena in nature, it appears to give a reliable index of production rates that can be used to compare one situation with another. Since there are still some unanswered questions concerning the interpretation of results in terms of the production by the plant cell, C^{14} data are best used in a relative rather than an absolute sense (*cf.* Rhode, Vollenweider, and Nauwerck, 1960).

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[3] Limnol. and Oceanogr., 4(1): 106–107.

Suspension of bottles in a lake at a variety of depths enables one to obtain a rather complete photosynthetic profile for the entire basin. Counting of phytoplankton for a comparable series of depths would be laborious and at best would give a static measurement of the phytoplankton crop, not phytoplankton production. The C^{14} technique on the other hand makes only modest demands upon manpower while providing a useful assessment of primary productivity. Since the field work does not require expert knowledge, it can be made a part of routine inventories on lakes and ponds.

Special applications of the technique have been made by certain investigators. Schelske[4] studied the influence of various combinations of nutrients and chelating agents upon photosynthesis in a marl lake by comparing the C^{14} fixation rates in bottles of lake water to which nutrients and chelate had been added with control bottles containing no additives. Photosynthetic rates were determined by the C^{14} method after the bottles had been incubated in the lake for a 7- to 10-day period. A similar use of the method was made by Goldman (1960) who tested the effectiveness of various nutrients upon the waters of Alaskan lakes by measuring C^{14} uptake rates after the incubation of algal cultures in the lake.

With the exception of these two studies, as yet the method has not been used to evaluate changes in production rates of lakes and ponds resulting from the addition of fertilizers and other chemicals. This would appear to be a promising application in the field of fisheries biology.

FOOD RELATIONSHIPS

Isotopes have been used in several different types of studies dealing with the feeding of aquatic animals and the food chains of aquatic communities. The manner in which radioisotopes pass through an aquatic food chain has been studied by Davis and Foster (1958). These authors followed the uptake by the invertebrate and fish fauna of a variety of radioactive waste materials from the Columbia River. They found that both adsorption and absorption are of major importance in the uptake of radioisotopes by plants, but that animals secure almost all of their radioactivity by ingestion of food. The concentration of radioactive substances in animals was found to vary between species, and fluctuated according to food habits and type of life cycle. They believe that in a flowing stream the specific activity of an isotope diminished along the food chain.

A variety of invertebrates have been labeled with isotopes and then used in feeding experiments (*cf.* papers cited below by Shekhanova, 1955; Tomiyama *et al.*, 1956; Kobayashi *et al.*, 1960). Trama[5] fed mayflies (*Stenonema*) algae labeled with P^{32}. Upon obtaining measurements of respiration and assimilation he was able to calculate the efficiency with which this herbivore converts food into living matter. Sorokin (reported by Zhadin, Kuznetsov, and Timofeev-Resovsky, 1958) used algae and bacteria labeled with C^{14} to study the nutrition of cladocera and tendipedid larvae. These studies showed that the midge larvae assimilate bacteria and blue-green algae and that cladocera assimilate bacteria and protococcus algae.

Pendleton and Smart (1954) labeled amphipods (*Hyalella*), ostracods (*Herpticypris*), and mosquito larvae (*Aedes*) with P^{32}. They introduced these labeled invertebrates into aquaria containing adults and fry of the least chub (*Iotichthys phlegethontis*). The chubs soon showed some radioactivity indicating that these three arthropods had been used as food. Nelson[6] studied the rate at which trout took up the radioactive phosphorus added to the water of an alpine lake in Colorado. He found that rainbow trout took up the isotope twice as fast as brook trout. He also noted that brook trout which had spawned in the lake took up the isotope about twice as fast as planted trout. Nelson believed these differences in uptake rates were due to differences in feeding and food habits.

Chipman (1959) has reviewed studies in which isotopes have been used to investigate foods and feeding activities of marine animals. An excellent example of studies of this type is the work of Rice and Smith (1958). These workers fed phytoplankton labeled with P^{32} to the hard clam (*Venus mercenaria*) and by measuring the rate of disappearance of the radioplankton cells were able to calculate the clam's filtering rate. Using this technique they were able to study the influences of a number of environmental factors upon filtering rates.

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[4] Schelske, Claire L. (1960) Preliminary report on the influence of iron, organic matter and other factors upon primary production of a marl lake. Inst. Fish. Res., Mich. Dept. Conservation, Rept. 1586 (unpublished).

[5] Trama, Francesco B. (1957) The transformation of energy by an aquatic herbivore *Stenonema pulchellum* (Ephemeroptera). Univ. of Michigan thesis, 80 pp.

[6] Nelson, Wesley C. (1958) The uptake of phosphorus P^{32} by the fish population. Progr. Rept., U. S. Atomic Energy Comm., Proj. No. AT-(11-1)-390.

FISH DISEASES AND FISH NUTRITION

Ionizing radiation is used on a large scale in medicine. The earliest application was X-ray for diagnostic purposes and therapy. The discovery of radium was next, and the most recent is the use of radioactive isotopes of many elements in diagnosis and therapy of various diseases. Rosenthal (1958) studied the uptake of calcium^{45} and strontium^{90} by wild guppies and an aberrant strain of guppies characterized by hereditary lordosis. Fish affected by this abnormality take up less Ca^{45} but contain it in larger quantity in the bones than the normal wild guppies.

LaRoche and Leblond (1954) used iodine^{131} to destroy the diffuse thyroid tissue of the Atlantic salmon (*Salmo salar*). This destruction is effected by the selective uptake of iodine by the thyroid gland. Though the work was done from the physiological approach, the method may offer a procedure of therapy for carcinoma of the thyroid such as was described by Gaylord and Marsh (1912).

McCay *et al.* (1936) established, through body analyses, that rapidly growing trout utilized dissolved as well as dietary calcium. That dissolved minerals could be an important source to fresh-water fish was shown by Wolf (1951), who raised trout on a "mineral-free" variation of his synthetic diet. Because there was confounding of mineral sources (food and water), little advancement in mineral nutrition of fish could be made using standard methods. The production and availability of radioisotopes and the development of tagging techniques for labeling and tracing minerals from specific sources provided a potent research tool. As yet, the major efforts have been applied to this field of mineral nutrition with practically no emphasis on the organic foods.

That contamination of fresh waters with radioactive wastes from atomic energy installations could cause selective concentration of radioactive materials in fish populations, either by the fish ingesting contaminated food or by direct uptake, was early recognized and investigated (Prosser *et al.*[7]; Higgins, 1950; Krumholz, 1956). Both the hard and soft tissues of aquatic organisms were found to concentrate radioactive ions.

Laboratory tracer experiments have been carried out under simulated natural conditions to investigate the metabolism of minerals. Since many of the natural foods of fish are excellent concentrators of minerals, it is possible to rear them in a suitable radioactive environment and then use the organism as labeled food. This method has been used with a variety of organisms, including *Daphnia* (Shekhanova, 1955), the sludge worm *Rhizodrilus* (Tomiyama *et al.*, 1956), and *Chironomus* larvae (Kudriavtzev and Pora, 1958). After *ad libitum* feeding, it is possible to measure the utilization and excretion by the fish of the particular nutrients formed from the radioisotope by the food organism. Kobayashi and Tomiyama (1959) and Kobayashi *et al.* (1960) have extended these studies to include the turnover of labeled phosphorus in *Rhizodrilus* and have determined the distribution of organic phosphorus fractions. Much of the phosphorus was converted to the organic forms.

Because there is uncertainty of the chemical nature of a labeled nutrient following metabolism by intermediate food organisms, and to eliminate *ad libitum* feeding, the Cortland Laboratory (Phillips *et al.*, 1957, 1958, 1959) has investigated the utilization of major and trace dietary minerals by feeding trout quantitatively labeled doses of calcium, phosphorus, and cobalt in capsulated synthetic foods. Concurrently with these diet experiments, this laboratory also prepared various representative synthetic waters and measured a normal direct uptake by trout of the previously-mentioned minerals and in addition chloride and sulphate. Dissolved calcium significantly contributed to structural growth.

TRACING MOVEMENTS OF WATER, POLLUTANTS, AND SEDIMENTS

The high degree of sensitivity with which isotopes can be detected has led to their use by oceanographers, hydrologists, and engineers to study water movements. An example of the extent to which an isotope can be dispersed in water and still be detected comes from a report of Ball and Hooper.[8] A Michigan trout stream was dosed with 1.5 milliliters of radioactive phosphorus (23 millicuries). Before it was added to the stream. this small quantity was diluted with 55 gallons of water and during a period of 30 minutes the mixture was fed at a constant rate into a stream having a flow of 37 cubic feet per second. Even though phosphorus^{32} is taken up rapidly in the stream, the radioactivity was detected at a downstream location 2½ miles away for a period of over 2 hours. A water activity approximately one trillion times smaller (1×10^{-12}) than the activity of the solution before dilution was counted after the water samples were concentrated.

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[7] Prosser, C. L., W. Pervinsek, J. Arnold, G. Svihla, and P. C. Tompkins. (1945) Accumulation and distribution of radioactive strontium, barium-lanthanum fission mixture and sodium in goldfish. Atomic Energy Comm., MDDC-496.

A review of uses made of isotopes to investigate problems of large-scale ocean circulation and transport has been published (National Academy of Sciences-National Research Council, 1957). Parker (1958) employed tracers to determine the eddy diffusion coefficients in a Massachusetts reservoir. A number of recent papers have discussed the use of isotopes to determine speed and direction of flow of ground water (Finkel' shteyn *et al.*, 1958; von Buttlar and Wendt, 1958; Halevy *et al.*, 1958). Simpson *et al.* (1958) treated sewage from Knolls Atomic Laboratory with 4.53 curies of P^{32} prior to its discharge in the Mohawk River. They then followed its movement with immersible Geiger-Müller tubes and by sampling. They found that the initial path of the sewage was strongly influenced by differences in density due to temperature. During the warm months cold sewage moved on the river bottom perpendicular to the river currents for the first 800 feet of travel. During cold months sewage rose to the surface and at times was moved upstream by wind. Near freezing the sewage first rose and then sank as its temperature approached 39° F.

MARKING AQUATIC ANIMALS

The marking of animals with radioisotopes is a rather obvious application of nuclear technology to ecological and systematic studies which has been frequently discussed in the literature but has found comparatively little use in aquatic biology. Isotopes have been widely used in the field of entomology for population studies, analysis of insect dispersion, transmission of disease, and insect control with insecticides (Jenkins, 1957). Pendleton (1956) and Griffin (1952) present discussions of the advantages and limitations encountered in marking animals with radioisotopes. These papers may also be consulted for details concerning isotopes that have been used and the dosages carried on radioactive tags.

Seymour (1958) has discussed the tagging of fish with radioisotopes. His paper should be consulted for a review of the regulations governing use of isotopes which would apply to a fish-tagging experiment. Seymour concludes that methods now in use for marking fish are generally more practical than isotope methods. There are four general limitations that would be encountered in tagging aquatic animals. First, penetration of radiation through water is poor. The shielding effect is so great that an aquatic animal could not be detected through more than a few feet of water, even though it was carrying a tag emitting energetic gamma radiations. Second, tags of high energy gamma radiation may, despite shielding, kill or disable the animal so that it does not behave as other members of the population. Thus it would be imperative that a study be made of the influence of the tag upon the fish before an isotope tag could be used in a population study. Third, a possible advantage of radioactive tags over other fish tags is that it may be possible to tag fish with an isotope tag at the egg or fry stage and follow their survival a number of years. Such a use would require an isotope of a long half-life. Fish carrying a radioactive tag with a long half-life may in turn present a serious health hazard depending upon the manner of tagging, the extent to which the species is used as food, and the likelihood that tagged specimens will be recovered by the public. Fourth, an isotope tagging technique which identifies individuals or groups within a tagged population, has not been worked out. This problem, however, does not seem to be insurmountable, since several possible methods might be employed.

It is clear that situations in which isotope marking might be used are either those in which there is complete control over the fish harvest or where the tagged fish can be handled without danger to the public. Remote areas might be used where there is little or no possibility of the isotope tag being accidentally ingested by humans. An isotope with a short half-life and one which gives off energetic gamma radiation would have the advantage of minimizing the health hazard and at the same time facilitating the detection of marked animals. Such tags, however, would find little use in solving some of the more challenging fish population problems.

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[8] Ball, R. C., and F. F. Hooper. (1959) Preliminary report on translocation of radioactive phosphorus (P^{32}) in a Michigan trout stream. Progr. Rept., U. S. Atomic Energy Comm., Div. of Biol. and Med., Contr. No. AT(11-1)-655.

Boroughs, Townsley, and Hiatt (1956) demonstrated that the amount of activity (strontium^{89}) within marine fish can be accurately estimated by external monitoring with the probe of a count rate meter. This would eliminate the time-consuming procedure of dissecting and ashing the fish to determine its activity. External monitoring would also allow tabulation of marked individuals without sacrificing members of the population.

D. P. Scott of the London, Ontario, Research Station of the Fisheries Research Board of Canada has furnished the authors with the following brief summary of some highly significant work in progress at this station on the use of radioisotopes for tagging fish:

> We simply empirically test the up-take and loss [from fish] of all gamma-emitting isotopes with half-lives longer than seven days. Any which are found to have a biological half-life longer than seven days would appear on the surface to have potentialities as marks. To date we have not tackled any of the pure beta-emitters but plan to do so in the future.

Scott and his group will soon publish a report on the possibility of using iron^{59} and caesium^{137} as short-term tags.

LICENSING OF ISOTOPES FOR RESEARCH

Licensing procedures and requirements for using radioisotopes in the United States are given in part 30, Title 10 Code of Federal Regulations.[9] This regulation provides for general licenses and specific licenses. It issues a general license to anyone wishing to use quantities of isotopes that do not exceed the amounts specified in the regulations. Quantities available under general license are adequate for many purposes. For example, the quantity of C^{14} specified under the general licensing procedure is 50 microcuries. The regulation allows as many as 10 such quantities to be on hand at one time. Thus under the general license one could possess as much as 500 microcuries of C^{14}. If C^{14} were to be used in productivity studies, 250 ampoules containing 2 microcuries could be on hand. The use of materials secured under a general license is subject to restrictions set forth in the regulations mentioned above.

Larger quantities can be secured by obtaining a specific license. Many universities and other agencies have a specific license. Application for a specific license must be made to the Atomic Energy Commission. Each application is judged on its own merits. Two important considerations in judging each application are the training and experience of the applicant in using radioactive materials, and the adequacy of protection against radiation hazards. Applicants should specify the maximum amount of material they will have on hand and how it is to be packaged. This may be an important consideration in approval of the application. For C^{14} work 2 or 3 millicuries packaged in ampoules containing 2 microcuries would provide an adequate supply of material for a considerable period of field work. Prospective applicants for a specific license should first secure some training and experience in using isotopes and in measuring radioactivity. This can be accomplished either through formal classroom training or by an apprenticeship with a qualified investigator. Experience can be obtained by first using generally licensed quantities.

FUTURE USES OF RADIOISOTOPES IN FISHERIES

Without doubt there will be a greater use of radioisotopes in fisheries laboratories as personnel trained to work with isotopes are recruited into this field. Although radioisotopes can aid researchers in only a small fraction of laboratory research problems, tracers can be extremely effective in many instances, *e.g.*, studying factors affecting the filtering rate of clams as carried out by Rice and Smith (1958). Use of radioactive materials in field studies will continue to be heavily restricted by health hazard considerations. Only those field studies where there is a minimum risk of public exposure will be allowed by the licensing agency. Two conditions might be expected to influence the extent to which isotopes will be licensed for future field investigations: (1) An increase in knowledge of the hazards associated with various types of radiation. Much remains to be learned in this field. Present standards are tentative and will be revised as more facts become available. (2) The extent to which the public accepts radioactivity as a part of everyday life. The teacher-training program recently started by the U. S. Atomic Energy Commission is a sign of progress toward broadening public understanding of radiation.

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[9] Reprints are available from the U. S. Atomic Energy Commission, Washington 25, D. C.

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Contributions of radionuclides to our understanding of Aquatic Ecosystems

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Introduction

Radionuclides provide a method of detecting chemical elements at lower concentrations than previously had been possible. The use of radionuclides does not require new experimental methods, only new techniques, principally of measurement. In the study of aquatic ecosystems radionuclides afford a means of tracing the movement of elements within the ecosystem and of observing the processes related to these movements. As an aid to understanding the ways in which radionuclides can be used, the advantages and limitations of the radionuclide method and the factors related to the biological accumulation of radionuclides are reviewed.

The Radionuclide method

Advantages. The principle advantage is that radioisotopes[1] can be detected by radiological methods in smaller quantities and usually more easily, more rapidly, and more accurately than stable isotopes can be detected by chemical, spectroscopic or spectrographic methods. For these reasons it is now practical to conduct many experiments that were not practical before radionuclides were available as tracers of chemical elements. Another advantage is that the amount of an element required in either laboratory or field experiments is less when the radioisotope of the element is used, and therefore disturbance to the ecosystem and interference with metabolic processes of individual organisms are less. A further advantage is that the use of artificial radioisotopes eliminates the question of how much of the element was present in the sample prior to the beginning of the experiment and how much was added during the experiment.

Limitations. Radionuclides are potentially hazardous and therefore responsibility for their safe handling and distribution is imposed upon the user. Recognition of this responsibility restricts the use of radionuclides in some experiments.

> The experimenter has the moral responsibility not to create situations of danger to others or to jeopardize the continuity of natural populations. This responsibility automatically eliminates the use of radioisotopes in labelling some kinds of food animals and high-level releases into non-control situations (PENDLETON 1956).

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[1] A radioisotope is defined as any radioactive isotope of a specific element; a radionuclide as any nuclide that is radioactive.

Seymour, A. H. 1964. Contributions of radionuclides
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There are some limitations in the use of radionuclides as tracers of the lightest elements. The radionuclide method is based on the assumption that plants and animals do not distinguish between stable isotopes and radioisotopes of the same element, but an exception may occur if the weights of the stable isotopes and radioisotopes are significantly different. For example hydrogen-3 (tritium) is an unacceptable substitute for hydrogen-1 in some experiments. Also, it is known that carbon isotopes behave differently, as demonstrated by phytoplankton, in which the uptake is slower for carbon-14 than for carbon-12. However this "isotopic effect" disappears for heavier elements as the relative differences in the weights of the isotopes decrease.

Factors to be considered in the biological accumulation of radionuclides

Radionuclides may adhere to the exterior surfaces of organisms or may be ingested. If ingested they may remain entirely within the alimentary canal or be absorbed into tissues. The mechanism of accumulation is difficult if not impossible to determine for one-celled and other small organisms, but the importance of the adsorption process is indicated by HOFFMAN and OLIVE (1961), who report that the accumulation of phosphorous-32 by *Daphnia* is proportional to the surface area of the organism. Whether the radionuclide is adsorbed to or absorbed by the organism is of little importance to the movement of the radionuclide in the food web as long as the radionuclide is available to the organisms at the next trophic level. The important considerations in the accumulation of radionuclides are biological availability of the radionuclide and the biological and environmental factors related to uptake and loss of the nuclide. These factors have been considered by KRUMHOLZ, GOLDBERG and BOROUGHS (1957) and DAVIS (1960) and are discussed below.

Availability. The availability of radionuclides for accumulation on or in organisms is determined by the chemical and physical states of the radionuclides in water, i. e., whether they occur as anions or cations and are in the ionic, colloidal or particulate state. The physical and chemical characteristics of sea water are more constant, by far, than those of fresh water but still are not well defined. Limited information suggests that in sea water most monovalent or divalent ions occur as cations; noble (inert) metals and metals of a higher valence state occur as anions. The physical state depends upon whether or not the solubility product has been exceeded. Experimental data show that elements of Groups I, II, V, VI and VII of the Periodic Table usually occur in sea water in the ionic state, whereas other elements occur generally in the colloidal or particulate state.

Uptake. Accumulation of radionuclides by adsorption depends upon the availability of the radionuclide, but concentration of a radionuclide in a tissue depends upon a physiological requirement for the nuclide as well. Thus, a radionuclide may be present in the water but is not concentrated by the organism.

One factor that affects the amount of radionuclide uptake is the chemical composition of the water. If stable isotopes of the same (or chemically similar) elements as the radioisotope are present in the water, then the accumulation of the radioisotope in the organism may be slight at high concentrations in water and great at low concentrations in water. For example, the uptake of cesium-137 by the oyster has been shown to be directly related to the concentration of cesium in sea water; on the other hand, WHITTAKER (1961) has shown that the concentration of radiophosphorous in fresh-water algae at low phosphorous levels in the aquaria is one million or more but only a few hundred or a thousand at high phosphorous levels. The uptake of an element also may be influenced by other elements in the water. KETCHUM (1939) found that the uptake of phosphorous by marine diatoms was increased when the nitrogen concentration was increased. Other environmental factors that have been demonstrated to affect the uptake rate of radionuclides are light, temperature, p^H, salinity and the volume of water per organism. The accumulation of radionuclides by aquatic organisms is also a function of age, growth and physiological condition of the organism.

Results of investigations

The literature on radionuclides in aquatic environments is extensive; however, for this review the information selected was limited to that which is related to the use of radionuclides as a means of understanding aquatic ecosystems. Bibliographies of special note include KLEMENT and SCHULTZ (1962); SCHWARTZ (1961); and the bibliographies in the papers by FONTAINE (1960) and by KUZIN (1960). The principal review articles used in preparation of this report include KRUMHOLZ et al. (1957); ZHADIN, KUZNETSOV and TIMOFEEV-RESOVSKY (1958); DAVIS and FOSTER (1958); HOOPER, PODOLIAK and SNIESZKO (1961); SEYMOUR (1961); and the summaries by KRUMHOLZ (1962) and by SEYMOUR (1962) of parts of the First National Symposium on Radioecology at Fort Collins, Colorado, in 1961 (SCHULTZ and KLEMENT, in press). Other references were noted in List of References on Nuclear Energy (International Atomic Energy Agency) and in Nuclear Science Abstracts (United States Atomic Energy Commission).

Most of the literature referred to in this report is related to fresh-water ecosystems but occasional reference is made to marine ecosystems when the subject describes a principle common to both systems.

The use of radionuclides has facilitated the study of water circulation, sediment distribution, and fish migrations as well as the movement of elements through ecosystems. Naturally occurring radionuclides, fallout radionuclides, radionuclides from reactor operations and radionuclides deliberately added to aquatic environments have been used for experimental purposes.

Water circulation. An example of the use of a naturally occurring radioisotope to determine water movement is the study of the distribution of radium-226 in the deep ocean. Radium-226 is a decay product of ionium (thorium-230) which is the second decay product of uranium-238. In the sea the salts of ionium quickly precipitate into the bottom sediments and in time decay to radium-226, part of which leaves the sediments and reenters the water. As a consequence, the amount of radium-226 in sea water is greatest at the bottom of the ocean and decreases towards the surface, thus providing a means for estimating the mixing of bottom ocean waters.

The horizontal movement of surface ocean water has been estimated by determining the presence of fallout radionuclides in water and/or plankton and in sessile or non-migratory organisms at known distances from the point of introduction of fallout into the ocean. Estimates made in this manner of the rate of advance of surface water in the North Equatorial Current of the Central Pacific Ocean range from 11 to 16 km a day.

An example of the use of radionuclides in a field experiment to measure water movement is reported by LIKENS and HASLER (1962). They were able to measure directly the rate and pattern of water movement in an ice-covered lake and to obtain information pertaining to the origin of this motion.

Radionuclides also have been used to trace the movement of ground water and of sewage and other wastes. The use of radionuclides to study the water diffusion processes in ponds, lakes or oceans has been little exploited but offers a great opportunity to obtain much-needed information. Solution of the diffusion problems, however, may not rest entirely upon the use of radionuclides. Recently a fluorescent dye, rhodamine B, which can be detected in fractions of a part per billion, has been used successfully for diffusion studies.

Bottom sediments. Radionuclides have been used in various ways in bottom sediment studies. In one experiment, the dynamics of beach sedimentation have been studied by tagging pebbles, sand, and sediments with radionuclides and following their movement. In other experiments, the exchange capacity of various clays and marine sediments have been investigated by making use of carbon-14 and hydrogen-3, tritium. Carbon-14 provides a rapid, reliable and efficient means for the analysis of adsorption phenomena, and tritium-labelled planktonic organisms, upon decomposition, provide a mechanism for study of the chelation process. In still other experiments, the availability of sediment-sorbed materials to marine biota has been the subject of study. DUKE, IBERT and RAE (in press) recognize the commonly accepted viewpoint that the sorptive properties of clay materials, diatom frustules and other common suspensoids provide a means by which ions of radionuclides can be transferred directly from the ocean water to bottom sediments without passing through the biota; however, they demonstrated that radionuclides may be more available to bacteria and filter-feeding organisms when attached to solid aggregates than if they remained in the ionic form. Also, the supposed scavenging properties of highly sorptive, precleaned clay were not demonstrated. Hence the importance of clay sediments in scavenging radioisotopes from ocean waters may be somewhat less than commonly believed.

Fish tagging. Fish and other organisms are tagged to determine their migration routes, daily movements and home ranges. Radioactive tags are better than conventional types of tags for some experiments and can be applied either directly by injection or indirectly by absorption from water or food. An example of the former type of application is the tagging of Alaska herring by the injection of a small bit of cobalt-60 wire into the body cavity (WILIMOVSKY 1961). The success of the experiment depends upon an efficient recovery of tags. The cobalt-60 tag was selected for this experiment because it is expected to be more easily detected than the magnetic tags which were used formerly in similar experiments.

Tagging by absorption of radionuclides from food or water provides a means for marking fish of all ages in practically unlimited numbers and with much less effort than is required for manually-attached tags. The choice of radionuclide depends upon the objective of the experiment. For some experiments beta-emitting radionuclides with short half lives will suffice; for others, gamma-emitting radionuclides with long half lives, such as Ce^{144}-Pr^{144}, are used. RUDAKOV (1958) tagged 15-gram carp by placing them for one hour in an aquarium with a specific activity for Ce^{144}-Pr^{144} of 1 mc/l. After one and a half months the tagged fish were identified easily and could be detected at a distance from the meter of 10—15 cm in water and 1 m in air. Other radionuclides used for tagging fish include calcium-45 and phosphorus-32 (KARZINKIN, SOLDATOVA and SHEKHANOVA 1959) and radioactive iron (SCOTT 1961).

Cycling of chemical elements. The cycling of phosphorus in lakes and ponds has been a favorite study of limnologists because the availability of phosphorus is believed to be a limiting factor in primary productivity and because an inexpensive isotope of phosphorus with a short half life (P^{32}) is readily available. The subject has been reviewed by RIGLER (1956), FOSTER (1959), and HOOPER et al. (1961). The conclusions from these three papers are summarized as follows: Phosphorus added to a pond is rapidly lost from the water and planktonic bacteria are primarily responsible; there is rapid exchange with plankton, mud, and rooted plants; phosphorus is continually passing from the epilimnion to the hypolimnion of stratified lakes through the sedimentation of seston; little of the phosphorus accumulated by bottom mud is released without agitation; some exchangeable phosphorus is lost to diatoms, which convert it to non-exchangeable phosphorus in organic compounds; and phosphorus as a fertilizer is available to the biota for a longer time when used with a combined mineral fertilizer.

Recently, WHITTAKER (1961) found that gross uptake of phosphorus was greater in oligotrophic aquaria than in eutrophic aquaria and in general the larger the animal the less and slower the uptake per unit mass. In another recent experiment, POMEROY (in press) evaluated the relative importance of biological and physical processes in the short-term turnover of phosphorus in natural waters. As a result of the addition of methylene blue (to block phosphorylation) and cyanide (to block respiratory metabolism) the short-term turnover of phosphate, between water and suspended solids, was stopped. Therefore the short-term turnover is believed to involve biological rather than physical processes.

The movement of radiophosphorus through a river ecosystem also has been studied (BALL and HOOPER, in press). Some of the results based upon three years of study on the west branch of the Sturgeon River in northern Michigan are as follows: Periphyton were found to have the highest specific activity with perhaps most of the phosphorus-32 located intercellularly; in no instance did measurements of macrophytes — algae, moss and vascular plants — reach the radioactivity levels of periphyton. The activity-density curves for the moss were consistently two or three times greater than for the algae or vascular plants. They concluded that the uptake of radiophosphorus could be followed on a time basis from the producers, to the filter-feeding primary consumers, to the periphyton scrapers, to the omnivores, to the detritus feeders, and ultimately to the carnivores.

Some elements other than phosphorus also have been used experimentally to study the movement of materials in aquatic ecosystems. PENDLETON and HANSON (1958) studied the absorption of cesium-137 by components of an aquatic community and found that the sites of maximum deposition were fish gonads, frog and waterfowl muscle, and plant roots and that cesium-137 is more mobile in mud than in soils. WILLIAMS and PICKERING (1961) using cesium-137 and strontium-85 confirmed the findings of others that the principal mode of accumulation of radiomaterials by fish in the food chain, from *Euglena* to *Daphnia* to bluegills, is through ingestion. Contrary to the above conclusion TOWNSLEY, REID and EGO (1961) believe that the principal mode of uptake of zinc-65 by marine fish is from sea water. In other experiments IVANOV studied the sulphite turnover processes in reservoirs (from ZHADIN et al. 1958). He found that the production of hydrogen sulfide in the surface layer of silt in one lake during the summer was 20 mg/l/day, also, that the conversion of sulphides to sulphur was principally a chemical process but that oxidation of sulphides to sulphates was principally a bacterial process. Another experiment with sulphur-35 demonstrated that sulphur ions are precipitated by ferric hydroxide flocculation (SUGAWARA et al. 1952).

The cycling of radionuclides in natural waters also has been studied by observing the distribution of radioactive wastes from large atomic-energy installations. One of the many papers that report the distribution in the aquatic environment of radionuclides released from the Hanford atomic plant into the Columbia River is DAVIS et al. (1958). More recently, OPHEL (in press) reported the movement of strontium-90 in Perch Lake near the Chalk River establishment, Atomic Energy Canada Limited, based upon five years of observations, 1956—1960. He observed a seasonal fluctuation of strontium-90 in lake water which was attributed to biological activity, that is, increased biological activity in the summer resulted in lower strontium-90 values in lake water. Strontium content in the bones of young perch *(Perca flavescens)* gradually increased during the period of observation and reached the equilibrium value during the fifth year. At this time the concentration value was 3,000. For other samples the concentration factors ranged from 200 to 3,900. The uptake by clams in the Clinch and Tennessee Rivers of strontium-90 released from the Oak Ridge National Laboratory has been reported by Nelson (in press). He found that the shells of fresh-water clams were good biological indicators of strontium and that the difference in minimum strontium content among species was due to inherited differences in the animal species, rather than to any differences in the strontium/calcium ratios in the environment.

The accumulation factors for various radionuclides expressed as the ratio of the concentration of radionuclides in the sample to that in the water differ for various groups of organisms. Zhadin et al. (1958) have summarized these data as follows:

Group of Organism	Accumulation Factor
higher aquatic plants	100's to 1,000's
benthonic invertebrates	100's to 1,000's
plankton	1,000's to 10,000's
detritus, fresh silt deposits	greater than 10,000
Elements	
sulphur	10's
strontium, germanium, cesium	10's to 100's
iron, cobalt, ruthenium	100's to 1,000's
phosphorus, zinc, yttrium, cerium	1,000's to 10,000's

The authors point out that these are approximate values and that there are many exceptions due to the accumulation of specific elements by certain organisms, for example, cesium by duckweed and strontium by molluscs and crayfish. Also, within the same organism certain tissues are accumulators of specific elements.

The radionuclides with the highest concentration in fish samples from the Columbia River below the Hanford plant are as follows: Na^{24}, Mn^{54} and Sr^{89,90} in bone; Cs^{137} in muscle; P^{32}, Fe^{59} and Cu^{64} in gut content; Sc^{46} and Co^{60} in spleen; Cr^{51} in blood and Zn^{65} in the retina.

Productivity. The greatest single use of radionuclides for the study of aquatic ecosystems is the use of carbon-14 to measure primary productivity. The fixation of tagged carbon by phytoplankton has become, in the last ten years, a common world-wide method for measuring primary productivity. A recent detailed description of the carbon-14 method and its limitations is given by Doty and Oguri (1959).

The need to increase the productivity of ponds and lakes by fertilization has long been recognized but the means of accomplishing this objective, especially at secondary and higher trophic levels, are not well understood. From the experience of agriculturists there is good reason to believe that the addition of small quantities of specific elements to aquatic environments will accomplish this objective. Also, there is some direct evidence. Goldman (1960) has shown that molybdenum was a limiting factor to primary productivity in Castle Lake, California; and Donaldson (1962) has shown that the addition of crab-cannery waste to an oligotrophic lake of Western Washington produced a threefold increase in the weight of trout, but it was not possible to identify the element(s) in the crab waste that were responsible for the increased growth. The use of radionuclides to trace the movement of mineral elements in the food web from the primary producer to the secondary consumer may provide the means of identifying the element(s) required to increase the production of fish in lakes and is another example of a way in which radionuclides can contribute to our understanding of aquatic ecosystems.

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TECHNIQUES FOR STUDYING MOVEMENTS OF VERTEBRATES IN THE FIELD

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INTRODUCTION

Labeling animals with radionuclides and tracing the movements of these animals with portable detectors is an effective method for studying certain aspects of animal behavior in a natural environment. This paper consists of a general description of the method and a review of its applications with vertebrates.

The first recorded use of radionuclides in tracing movements of animals is reported by Tomes and Brian (1946). They labeled Elaterid beetles of the genus Agriotes with radium sulfate sandwiched between aluminum discs which were cemented beneath the elytra. Labeled beetles could be located under four inches of soil with a Geiger-Mueller rate meter.

Griffin (1952) published the first account of the use of radionuclide labels to study vertebrate activity. He obtained data on nest-attentiveness of a labeled Semipalmated Plover (Charadrius semipalmatus)

Radionuclide labeling is particularly useful for studying animals which are secretive in their movements. For example, it is difficult to observe small mammals or amphibians living in areas with dense vegetational cover. Individuals marked by the conventional methods of toe-clipping or banding are difficult to relocate, whereas animals labeled with radionuclides are relatively easy to locate in this type of habitat. Similarly some animals that spend all or part of their lives underground may be studied by this method.

GENERAL DESCRIPTION OF METHOD

In general the technique consists of placing a small amount of radionuclide on an animal in such a way that the animal is not seriously injured by the radiation and behaves in a normal manner. After being labeled the animal is released in its home range and its movements are followed by periodically scanning the area with a portable detection device. In most cases workers have made periodic checks at 12-or 24-hour intervals of the animal's location. In a few instances labeled animals have been tracked continuously for short periods of time (Godfrey, 1955; Green and Spinks, 1955).

This method of labeling animals has both advantages and disadvantages. The two most significant advantages are that in many situations observations can be made without interfering with the natural behavior of the organism and that labeled animals can be located without actually being seen by the observer. Another advantage is that radioactive labels are frequently not detectable by the labeled organisms or by predators that might prey differentially upon marked animals.

Use of radioactive materials which are metabolically incorporated into the tissues of the organism provides several additional advantages. Animals may be labeled and studied without ever being seen or handled by the observer. Many individuals of a population can be marked with a minimal effort if the radionuclide is administered to the organisms through their food. In these cases the radioactive label becomes a part of the animal during the course of the experiment.

A further advantage of certain metabolically incorporated radioactive material is that the nuclide can be transferred to young across the placenta (Finkel, 1947) and to chicks through the egg (Driggers et al., 1951; McCabe and LePage, 1958; Spinks et al., 1949). This type of transfer may be useful in studying dispersal of young from the place of birth or for the identification of specific litters or broods.

Portions of certain metabolically incorporated radioactive labels are eliminated in feces and urine. These signs may then be used to indicate the presence of the labeled animal.

The use of radionuclides in field studies has numerous disadvantages. One of the most serious is that of potential radiation hazard. The scientist must consider the possibilities of danger to himself and other human beings as well as to the ecosystem in which he is working. The choice of a study area must take into account not only the range of the species being labeled but also the range of possible predators on that species.

Standards for safe handling of radioactive material are available from the National Bureau of Standards and papers on health physics can be obtained from the Division of Technical Information, U. S. Atomic Energy Commission. Anthony and Norris (1946) and Comar (1955) discuss some of the problems of safety while injecting animals with radionuclides.

The effects of radioactive labels on the individual animal are likely to be more significant to the investigator than the over-all effects on the ecosystem. One must use extreme care to minimize the chances of radiation injury affecting the behavior and movements of the labeled organism. Control studies with non-radionuclide labeled animals should be included in investigations whenever possible.

Griffin (1952) gives a detailed discussion of the calculation of the radiation dose to a labeled animal and its likely physiological effect. His evaluation is based in part on the assumption that the labeled animal will have approximately the same threshold for radiation injury as the human skin. He concluded that the maximum permissible dose for "wild birds" would be 1,000 roentgens.

In evaluating the effects of a radioactive label one must consider the label as producing whole-body radiation which may cause injuries at lower dose rates than when radiation is restricted to a portion of the organism (Claus, 1958).

Effects of a given amount of radiation would probably be lower on poikilotherms than on homiotherms due to the comparatively low body temperature of the former during extended periods of the year. This concept is supported by studies by Patt and Swift (1948) who found that survival time of frogs (Rana pipiens) exposed to x-radiation could be prolonged by maintaining them low temperatures.

A somewhat analogous situation might be expected to exist between survival of hibernating and non-hibernating mammals. The onset of radiation damage was delayed but not prevented when marmots (Marmota monax) (Brace, 1952) and ground squirrels (Spermophilus tridecemlineatus) (Doull and Du Bois, 1953) were irradiated while in hibernation.

Tester, J. R. 1963. Techniques for studying movements of vertebrates in the field. pp. 445-450. In: Radioecology. (V. Schultz and A. W. Klement, Jr., eds.). Reinhold, New York, New York.

Another disadvantage to this method of labeling vertebrates is that it is difficult to distinguish between labeled individuals when there are many in the same area. It is possible to identify a few animals positively when labels of different strengths are used. Variation between labels should be in the order of 100 microcuries.

Griffin (1952) and Pendleton (1956) discuss in detail these and other advantages and disadvantages of using radionuclides to trace animal movements.

The selection of the nuclide must be based on the nature of the experiment with special consideration being given to the organism and its environment. Choice of an inert or metabolic-incorporated label must be made and characteristics of available radionuclides such as type and energy of radiation, physical half-life, biological half-life (time in which animal eliminates one half of administered dose by regular processes), and toxicity must be known.

In most vertebrate tracking studies an inert nuclide emitting gamma rays at an energy greater than one million electron volts would be preferable. This type of radiation could be detected at a greater range and through more intervening soil, water, or vegetation than weak gamma or alpha or beta radiation. In most cases alpha and beta radiation increase the radiation dose to the organism without facilitating the tracking of the animal. For inert labels a nuclide with a physical half-life in the range of 100 days to several years would probably be most appropriate.

Pendleton's (1956) review and bibliography should be examined prior to selection of a nuclide.

When an inert label, such as a piece of metal wire or rod, is desired the values of encapsulating must be considered. Griffin (1952), Godfrey (1954), Karlstrom (1957), Linn and Shillito (1960), and others have encapsulated labels in lead, aluminum, nickel, and other materials to facilitate handling of the nuclide and to shield the organism from beta radiation. Breckenridge and Tester (1961), Kaye (1960, 1961), and others have successfully used wire labels without encapsulation. In studies where the radioactive label emits large amounts of beta radiation and where the label must remain on the animal for extended periods of time encapsulation may be desirable. My investigations with tags containing 100 microcuries tantalum-182 used over one year on three species of Bufo indicate that encapsulation is not necessary when genetic damage can be ignored.

Techniques of labeling individuals vary considerably but can be logically separated into methods of attaching inert labels and methods of incorporating metabolic labels. Leg rings with radioactive material attached have been used on birds and mammals by Godfrey (1954, 1955), Griffin (1952), and Linn and Shillito (1960). Nora Croine-Michielsen of the University of Leiden marked small mammals with silver leg rings made radioactive by neutron activation in a reactor (Linn and Shillito, 1960). Breckenridge and Tester (1961) and Kaye (1960) used hypodermic needles with stylets for inserting wire labels subcutaneously in toads and mammals while Karlstrom (1957) labeled amphibians by cutting the skin and inserting a label with a forceps.

Jenkins (1954) applied a metabolically incorporated label to a small mammal by feeding "spiked" food whereas Miller (1957) injected radioactive material in similar animals to obtain longer retention in the body. McCabe and LePage (1958) made intramuscular implantations of gelatinous capsules containing calcium-45 in birds. Rapid administration of labels to numerous individuals could be facilitated by the use of oral capsules or implantation guns available from medical supply houses.

Problems of detection of labeled animals are minimized by using the most sensitive portable instrument available to the study. Instruments with directional shields or with electronic filters capable of reducing the response to radiation with energies above and below that emitted by the nuclide would be desirable. These modifications would cut out some background radiation resulting in an improved signal-to-noise ratio. My own preliminary tests with one-inch lead directional shields attached to the probe of a scintillation counter have not shown any increase in range of detection on 100 microcurie tantalum-182 sources. It is possible that the amount of shielding required to bring about substantial increase in detection distance would be too heavy for a portable instrument.

Distances at which labels can be located vary with the amount of radionuclide, the energy of radiation of the nuclide, and the amount and atomic weight of substances between the label and detector. Griffin (1952) discusses the practicable range of detection and gives a formula for its determination. Karlstrom (1957) conducted experiments on the range of detection of various quantities (20 to 2,800 microcuries) of cobalt-60 buried at selected depths in loam topsoil.

Detection distances reported in the literature vary from a few inches for feces and urine containing phosphorus-32 (Miller, 1957) to 23 feet for a 2,800 microcurie label of cobalt-60 with only air intervening between the label and scintillation counter (Karlstrom, 1957). This level of radioactivity was considered too high to allow use of the label on an animal. Labels of 100 microcuries of tantalum-182 were located on the ground surface from 15 to 20 feet while a buried toad carrying a four-month-old label (100 microcurie source initially) was located 22 inches deep in silty clay loam by Breckenridge and Tester (1961). We were able to detect animals marked with relatively undecayed tantalum-182 in 16 inches of water from a distance of four to five feet.

Labeled animals can be located with scintillation or Geiger-Mueller counters by systematic coverage of a study area or by random searching. Karlstrom (1957) discusses these methods and their merits and applications. The development of an automatic system for tracking and recording the movements of a labeled vertebrate similar to the device designed by Green and Spinks (1955) for following soil-inhabiting wire worms would be a major contribution to movement-study techniques.

The following portion of this paper consists of a review of methods used to study vertebrate movements utilizing radionuclides presented by phylogenetic classes.

FISH

The marking of fish with radioactive labels presents serious safety problems and, consequently, the technique has been used in only a few instances. Several of these studies were conducted in the U.S.S.R.

Carp (Cyprinus carpio) and sturgeon (species not given) fry were labeled with phosphorus-32 by Shekhanova (1955). Carp fry 10 to 20 millimeters long were labeled by placing them in water (amount not stated) containing 220 microcuries of phosphorus-32 for two hours. Labeled individuals could be identified as long as 77 days after labeling. Sturgeon fry were found to pick up less phosphorus-32 than carp. Therefore, they were fed oligocheates which had been fed on a yeast moistened with a sodium salt solution containing phosphorus-32. The fish were fed for one to two days on labeled food and then considered labeled. A total of 72,500 sturgeon fry were successfully labeled by this method.

Karzinkin et al. (1959) used essentially the same technique to label 106,000 young sturgeon (Acipenser güldenstädti) to study migration.

A more simple technique for labeling is discussed by Bogoiavlenskaia (1959) who added calcium-45 directly to the surrounding water. He found that the physiological uptake of the nuclide resulted in an accumulation in the bony structures of young sturgeon (duration of exposure not stated in translation). The recommended dosage is 300 microcuries calcium-45 per liter of water when the concentration of stable calcium is between 43 and 72 milligrams per liter. This dosage served as a label with a useful life of approximately one year.

In North America radionuclides have been used to study the population dynamics of Alaska herring (Clupea harengus pallasi). Wilimovsky (1961) presents a detailed description of the methods of labeling and detection and of the safety features of the system. In brief, Alnico V magnetic rods 0.5 inches long and 0.125 inches in diameter containing cobalt were numbered, imprinted with a return address, and gold-flashed. Rods were then neutron irradiated to produce cobalt-60. Labels were then coated with transparent polyethylene and injected into the abdominal cavity of the fish by means of a specially designed injector. Labeled herring are recovered from the commercial catch by equipment installed at processing plants. The label consists of ten microcuries of cobalt-60 and the recovery equipment is designed to be 100 per cent effective in removing labeled fish from the catch.

Scott (1961) successfully labeled 10- to 20-centimeter trout (Salvelinus fontinalis) by injecting one milliliter of solution containing 1.0 microcurie of iron-59 into the body cavity of each. The iron chloride solution was diluted with highly acid acriflavine hydrochloride before injection to prevent infection in the fish. Labeled fish were detected by placing a needle scintillation probe over the heart-liver region and counting with a portable rate meter or by placing the specimens in a circular tank with a detector at the center. The first method is faster where only a yes or no answer is required but involves more handling of each individual than the tank method.

Other methods for labeling fish with radionuclides and a review of the regulations governing the use of radionuclides which would apply to fish-labeling are presented by Seymour (1957). He concludes that radionuclide methods are generally not practical for labeling fish. Hooper et al. (1961) state that the only situations in which radionuclide labeling might be used are those in which there is complete control over the fish harvest or where the labeled fish will not constitute a public hazard. They suggest that radioactive labels would be superior to other methods in labeling at the egg or fry stage and following survival provided the preceding conditions can be met.

AMPHIBIANS

Use of radioactive labels in amphibians was initiated by Karlstrom (1957) who marked Yosemite Toads (Bufo canorus) with 20 to 30 microcuries of cobalt-60 contained in lead capsules. He was unable to locate any toads in hibernation sites four months after labeling and concluded that high background radiation and the comparatively low strength of his labels were responsible.

In laboratory experiments on survival of four species of western Bufo he found that many of the labeled toads lived long beyond the predicted period. For example, an adult male California Toad (Bufo boreas halophilus) survived 19 weeks exposure to 800 microcuries of cobalt-60 and two California toads carrying 2,000 microcurie cobalt-60 labels survived six and 14 weeks, respectively. Karlstrom states that the cause of death of these animals is unknown and that radiation "possibly contributed to the relatively early death."

Breckenridge and Tester (1961) report a high degree of success in following movements of the Manitoba Toad (Bufo hemiophrys). Animals labeled with 100 microcuries of tantalum-182 were followed during the summer for periods ranging from two to 90 days. Hibernation sites of six individuals were located in fall and the movements of these toads were followed until emergence eight to nine months later. Growth rates, movement, and behavior of non-labeled control animals and tantalum-182 labeled toads were similar in all respects.

At present we are securing depth determinations of burrowing animals by inserting three-inch fiberglass tubes into six-foot vertical holes dug in the soil about 12 inches laterally from the toads. The tubes, closed at the bottom to exclude water, are installed at the time the hibernation sites are located. The probe of the scintillation counter is lowered into each tube and the depth of the labeled toad is considered to be the depth at which the maximum radiation intensity is detected.

In our studies of the Plains Toad (Bufo cognatus) and the American Toad (B. terrestris americanus) we have had difficulties in relocating labeled individuals after several months. Plains Toads travel long distances and apparently most of our labeled animals have moved beyond the area which we can search. American Toads in our study area move comparatively short distances but spend most of their above-ground lives in dense brush and forest. The practical difficulties of searching in this habitat have prevented us from relocating most of the labeled individuals.

These results emphasize that behavior patterns of the organism and physical features of its habitat must be considered in the design of radionuclide tracking studies.

REPTILES

The only study of reptile movements using radioactive labels that I know of is currently being conducted by William Nelson of the University of Minnesota (personal communication). He is using essentially the same techniques and equipment developed by Breckenridge and Tester (1961) to investigate behavior of the Black-banded or Prairie Skink (Eumeces septentrionalis septentrionalis). His 100 microcurie tantalum-182 labels, 0.020 millimeters in diameter and 5.0 millimeters long, are injected subcutaneously in the mid-dorsal area and the place of injection is covered with a drop of collodion.

The animals under observation occupy a sandy ridge approximately 600 feet long and 55 feet wide adjacent to a small lake. The radionuclide labeling technique had enabled Nelson to follow individual skinks through two breeding seasons and to locate numerous underground nests and hibernation sites. The yearly range of movement of individual animals varied from about 15 feet for some females to 350 feet for one male. He attributes his success in keeping the labeled animals under observation to this comparatively small home range and to the tendency of the skinks to nest and hibernate at shallow depths in the soil.

BIRDS

Griffin (1952) labeled birds by attaching aluminum capsules containing zinc-65 (quantity not reported) to conventional bird bands in a study of nest attentiveness. A recording Geiger-Mueller rate meter with the tube buried near the nest was used. The apparatus was used primarily with the Semipalmated Plover and provided a continuous record of the periods when the labeled bird was present at the nest.

A somewhat similar system was developed by the National Research Council of Canada for the Canadian Wildlife Service to study nest attentiveness of Mallards (Anas platyrhyncos platyrhyncos) (Alex Dzubin, personal communication). A strontium-90 source was placed on one side of a nest and the tube of a recording Geiger-Mueller rate meter was placed on the opposite side. When the hen was on the nest the beta radiation was shielded from the counting tube and the record showed a lower count rate than when the hen was away. Numerous difficulties such as amplifier breakdown and "stray" vegetation interfering with the count rate led to abandonment of the techinque.

James Bendell (personal communication), University of British Columbia, reported labeling Blue Grouse (Dendragapus obscurus) with 500 microcuries of rubidium-86 attached to a standard patagial wing band. He was unsuccessful in locating these birds on their nests and attributes this to the difficulty of following the line of flight of a female returning to her nest. The range of detection with a Geiger rate meter was five to ten feet.

An indirect method of labeling progeny of specific females with radionuclides has been developed by McCabe and LePage (1958). They implanted calcium phosphate pellets containing calcium-45 in the breast muscles of Ring-necked Pheasant (Phasianus colchicus) hens prior to nesting to measure the contribution of the progeny of the released hens to the hunting take in the fall in Wisconsin. The nuclide was passed to the eggs and when leg bones of harvested birds were examined those bones from progeny of the labeled hens could be detected.

Tests on young from labeled hens showed significant accumulation of calcium-45 in the leg bones but extremely little in the breast muscle. McCabe and LePage (1958) concluded that eating the birds would not be in any way harmful.

I am currently initiating an investigation using modifications of this technique to analyze parasitic egg-laying in Redheads (Aythya americana). Individual hens in an enclosed study pen will be labeled with a specific radionuclide or combination of nuclides at the start of the 1963 breeding season. The radionuclide will be metabolically incorporated by the hen and some will be transferred to her eggs. The source of each egg will be determined by the energy of gamma radiation using a gamma ray spectrometer with a pulse-height analyzer. This technique will provide data for evaluation of the role of different age classes in parasitism and for analysis of the laying and incubation behavior of individual females.

MAMMALS

More studies utilizing radionuclide labels have been conducted on mammals than with any other class of vertebrates. All of these investigations have dealt with "small" mammals and both metabolically incorporated and inert labels have been used.

Jenkins (1954) fed a female lemming (Lemus sp.) 250 microcuries of phosphorus-32 mixed with rolled oats (amount not stated) and found that during the one month of study the animal could be easily identified in the field at a distance of eight feet with a Geiger-Mueller rate meter. Droppings from this animal containing the label served to determine its range of movement. This method facilitated the collection and study of lemming ectoparasites since the host could be located at feeding sites, middens, and resting places. One month after being labeled the lemming gave birth to a normal offspring which was labeled with phosphorus-32.

Home ranges of Meadow Mice (Microtus pennsylvanicus) were studied by Miller (1957) who injected phosphorus-32 into the animals and traced movements by detecting the nuclide in excretions on metal dropping boards distributed in the field.

In preliminary tests she injected House Mice (Mus musculus) with 200 microcuries of phosphorus-32 to determine the length of time the droppings would be labeled. For two weeks following injection any group of five fresh droppings from the labeled mice could be identified as labeled with a Geiger-Mueller rate meter at a distance of five centimeters.

Field studies revealed that both urine and droppings from labeled Meadow Mice contained phosphorus-32. Cleaning of the dropping boards in the field was difficult and the ultimate solution was to remove the phosphorus-32 contaminated boards from the field and replace them with new boards.

The rate of movement of food through the digestive tract was apparently spasmodic since some feces were high in phosphorus-32 and others were low or lacking. Miller (1957) concluded that 200 microcuries of phosphorus-32 was inadequate because of detection difficulties and recommends levels of 400 microcuries for animals the size of Microtus.

Several successful studies of movements of small mammals using radionuclide labels and a portable Geiger-Mueller rate meter have been reported by Godfrey (1953, 1954, 1955). She located 85 nests of Field Voles (Microtus agrestis) after labeling a large number of pregnant females with 100 microcurie tags of cobalt-60 held in a plaster of Paris mixture attached to a metal leg band (Godfrey, 1953).

European Moles (Talpa europea) were labeled for periods as long as three months with 80 microcuries of cobalt-60 contained in a metal ring fitted around the base of the tail (Godfrey, 1955). A Geiger-Mueller tube was mounted at the end of an eight foot bamboo pole so that animals could be located from a distance of at least ten feet. Labeled individuals could be readily located even when one foot below ground. The small home range (approximately 1/4 acre maximum) and slow movement of this mole made detection of its exact position relatively easy.

Kaye (1960, 1961) used comparatively large quantities of labels, varying from 700 to 4,500 microcuries of gold-198 to mark Eastern Harvest Mice (*Reithrodontomys humilis humilis*). Four animals were labeled with ten-millimeter pieces of 20-gauge wire in a study of movements and nest sites. Detection distances with a Geiger rate meter varied from 9 feet with a 700 microcurie label to 20 feet with 4,500 microcuries. The latter label was considered too large because the radiation intensity exceeded the capacity of the rate meter and made precise location of the animal difficult. He found headphones useful with his detector since increases over background were audible before becoming visible on the meter.

Other studies reviewed here suggest that labels in quantities used by Kaye (1960, 1961) might cause severe radiation damage to the mice. He does not mention this possibility or the effect the radiation might have had on natural behavior.

Linn and Shillito (1960) described rings containing radioactivity for use on shrews. Pieces of cobalt rod sheathed in nickel were irradiated to produce 50 microcuries of cobalt-60 and soldered to ordinary leg bands. The nickel and solder protected the animal from beta radiation but did not prevent detection of the gamma radiation by which the shrews were traced.

Another method of labeling shrews reported by Linn and Shillito (1960) is that used by Miss N. Croine-Michielsen of the University of Leiden. She tagged *Sorex araneus* with silver rings containing 200 microcuries silver-110. No beta radiation shield was used.

Homing and migration of bats of several species have been investigated using bands containing a radionuclide. Punt and Van Nieuwenhoven (1957) attached 250 microcurie rods of antimony-124 two by one millimeter to aluminum leg bands. Movement of bats within a cave and between caves was determined by periodically surveying the caves with a Geiger-Mueller rate meter with the tube mounted on a five meter extendable rod. Animals could be located even when in crevices out of sight of the observer.

Gifford and Griffin (1960) labeled bats with five microcuries of iodine-131. A solution containing the nuclide was poured into a flange of metal attached to a leg band. After the liquid had evaporated glue was spread over the remaining material and the flange was crimped against the main body of the band. Labeled bats could be located at distances up to one meter.

SUMMARY

A brief histroy of the use of radionuclides in tracing movements of animals is given and suggestions for use of this technique are made. The method consists of placing a small amount of radionuclide on an animal, releasing it in its home range and following its movements by periodically scanning the area with a portable detection device. Advantages and disadvantages of this method are discussed.

Methods used to study movements of fish, amphibians, reptiles, birds, and mammals utilizing radionuclide labels are reviewed.

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Use of tracer techniques for the study of biogeochemical cycles

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INTRODUCTION

It is natural that most contributions to this first international symposium on ecosystems should have centred on transfers of energy. Other unifying themes that relate ecology and other disciplines deserve equally intensive review during future symposia. Yet time requires that these themes be illustrated here by only a few striking examples.

One unifying theme which is closely related to energy transfer is the transfer of chemical elements. I agree with Dr. Ovington that transfers of both energy and nutrients should be considered together, or at least one after the other, in ecosystem investigations like those proposed for the International Biological Programme. In accordance with this symposium's orientation toward novel methods, I shall shortly discuss some applications of radioactive isotope tracers to studies of biogeochemical transfer in trees and forests.

In advance, however, I should note agreement with Dr. Blackman and others, that elaborate apparatus and tracers are by no means necessary for valuable measurements of dry-matter production. Nor are tracers essential for sophisticated mathematical models of productivity, as by growth analysis methods. Indeed, such analyses furnish a logical core for deriving productivity rates for the IBP. I would prefer also to see these methods extended for comparing agricultural monoculture with significant natural communities at most research stations of the Programme. Practical methods for doing this have been demonstrated by Ovington (e.g., 1962, 1965), Whittaker, Kornas, and others.

Symposia like the present one should encourage suggestions that will help official IBP committees to recommend biological physical and chemical measurements that are suitable for standardized, or at least intercalibrated, comparisons at many stations, large or small. Also important is the need for connecting results in terms of critical comparisons of model parameters for any network of productivity stations. We need truly ecological and geochemical as well as physical and mathematical hypotheses to test with the aid of these models.

Investigations of energy relations discussed this week furnish one necessary basis for making such comparisons. Efficiencies in fixation of solar energy in organic matter offer fundamental criteria for comparing ecosystems with other natural systems and with machines. Calories and power (caloric flow per unit time) furnish unified scales for comparing the flow of radiant energy and heat with the flow of energy in organisms, populations and communities. Micro-environments created by the transfers of heat, organic material, and water of course impose certain limits on primary production. They limit patterns and rates of transfer of organic energy and material through the network of living and non-living compartments which constitutes the ecosystem.

Nevertheless, the flow of energy and the very existence and role of the living species in the ecosystem depend on the flow of nutrients. The quality of organic material, e.g., in protein, nitrogen, and certain other elements, is as important to measure as is the dry weight per unit area, which is used to convert ecosystem measurements to protein or nitrogen per unit area.

The burden of analysis to furnish even a static chemical inventory of a fairly simple ecosystem means that the places and times for such chemical study will have to be selected carefully, with due regard for both climatic and soil factors limiting production. Fortunately, investigations summarized by Ovington (1962, 1965), by many Soviet soil scientists, Japanese ecologists, and others show that chemical inventories of natural ecosystems are feasible, and very instructive. Reviews of such work show that static inventories of nutrients can be supplemented by inferences about

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Olson, J. S. 1968. Use of tracer techniques for the study of biogeochemical cycles. pp. 271-288. In: Functioning of Terrestrial Ecosystems at the Primary Production Level. (F. E. Eckaedt, ed.). Unipub, New York, New York.

flows of various elements, as well as of dry matter and energy.

Many difficulties still accompany a complete modelling of chemical flow through an ecosystem. The role of isotopes is to help overcome some of these difficulties by furnishing information that is impractical, if not impossible, to get in other ways. We shall note several steps by which tracers can be used, in conjunction with other methods, for approaching our ultimate goal of more insight regarding the functioning of ecosystems.

Now what do we mean by the "state" of an ecosystem? One meaning that is perhaps most useful for this symposium is essentially to specify the distribution of pertinent variables among major parts of "compartments" of the system. I shall start like Professors Monsi, Cowan, and Milthorpe separating several layers even within the same kind of plant but will later find it sufficient for nutrient or isotope cycling studies to deal only with the major compartments (foliage, wood, bark, and roots) of a major species and the litter mat, and one or more pools of soil material, as Professors Ovington and Rodin have already discussed.

Just as Dr. Gates specified the temperature and other physical variables of a leaf as a point in multidimensional space, it is only slightly more taxing for the imagination to think of the contents of an element, like carbon, nitrogen, or cesium, for example, in n compartments of an ecosystem as representing a point in n-dimensional space. The ordered set of co-ordinates $(v_1 v_2 \dots v_n)$ can be considered as a vector in n-space. This point or vector in space shifts through time by the addition of many small vectors representing increments of production (or loss), e.g., the addition or loss of atoms, or packages of atoms such as leaves or tree boles.

TRANSFER MODEL

One step in tracer methodology is just to show whether tagged atoms introduced in one part, or compartment, of an ecosystem move to other parts, in detectable or significant quantities. If they do, then promptness of first appearance, and transfer rate per unit time become important. Often rates are expressed as a proportion p_{jk} of the material already in part j which move to part k. If we have conceptually abstracted our system as a compartment model with n boxes, then we should ideally like to specify a table (or matrix P) showing the proportion p_{11} of the constituent already in compartment 1 (row 1 of the table) which remains in compartment 1 and the p_{1k} which should move into compartments $k: 2, 3, \dots, n$ in some (very short) increment of time. Similarly, p_{22} expresses the proportion in compartment 2 which remains there, and p_{2k} the proportions which move, and so on, until all n rows of P are filled out.

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \qquad (1)$$

The terms $p_{11}, p_{22}, \dots, p_{nn}$ on the main diagonal of this matrix (p_{jj} or p_{kk} or p_{jk} where $j = k$) thus represent proportions of the constituent which remain in the same compartment.

Restating the model in terms of probabilities, the tracer atoms which are introduced in part $j = 1$ (say) start moving into other compartments, subject to an element of chance. Early measurements of the radioactivity in these compartments may furnish estimates of the probability that a randomly chosen atom moves to the second, or the kth compartment, or remains in the original compartment. As soon as appreciable transfer has taken place, atoms start moving from the second compartment to the kth, and perhaps also back to the first if 1 and 2 are indeed involved in a cyclic exchange rather than a one-way turnover out of compartment 1. In order to make explicit allowance for export from the local ecosystem, the nth and even $(n - 1)$th compartment, etc., may represent various losses from the system. There may or may not be negligible probability p_{nk} that atoms once exported from the local system will return to it.

If we take a stepwise view of changes in the numbers v_k of atoms of our constituent in the kth compartment of the system for a sufficiently short time step, Δt, the expected number that remain from the last preceding stage (time $t - 1$) is $v_k^{(t-1)} p_{kk} \Delta t$; $v_1^{(t-1)} p_{1k} + t + v_2^{(t-1)} p_{2k} \Delta t + \dots$ for all terms in the kth column of matrix (1), besides the one involving p_{kk} that was considered. All terms together then represent the expected number of atoms at time t:

$$v_k^{(t)} = \sum_{j=1}^{n} v_j^{(t-1)} p_{jk}. \qquad (2)$$

(In different words, we can represent the state of the system more briefly as a vector $V^{(t)}$ with n co-ordinates given by equation 2. The expected value of this state is given by the matrix product of $V^{(t-1)}P$.)

Discussion of a similar deterministic model for changes in carbon (Neel and Olson, 1962), radionuclides (Olson, 1963*a*, 1965) and dry-matter production (1964) is given elsewhere.

Sheppard (1962) explains elaborations of the compartment model approach, with important distinctions between equations for the number of tracer isotope atoms, and number of atoms of the tracer per unit of the element being tagged.

ELEMENTAL CYCLES: SMALL, MEDIUM, AND LARGE

Tracer isotopes can help to evaluate the probabilities of transfer given in matrix (1) for ecosystems ranging in size from the individual plant-soil (or microbe-medium) system to the biosphere as a whole.

Plant physiologists and agriculturists have long used tracers first to show rapid, small-scale transfers by contact exchange, active metabolic uptake and excretion, and translocation (de Hevesy, 1947; Stout and Hoagland, 1939; Stout *et al.*, 1947; Burris, 1950; Biddulph, 1955; Kursanov, 1955; Burton, 1957; Vlasyuk and Manorik, 1957; Fried, 1957; Fried *et al.*, 1958; Stenlid, 1958; Walker and Barber, 1961). These studies furnish insight regarding individual terms p_{jk} in the chemical transfers of a whole crop or other community. Usually an income-loss budget for the ecosystem has not been pertinent for the question asked by the physiologist. Hence there is still a paucity of data relating the inventories on a unit area basis (v_k) and the transfer probabilities (p_{jk}) which bring about changes in the inventory.

Environmental contamination by radioactive fall-out and nuclear wastes has extended the physiologist's interest to many trace elements besides those which are nutrients (Stout *et al.*, 1947; Klechkovsky, 1957, and many others). Monitoring has increasingly been expressed on a unit ground area basis, and has led interpretations to differentiate between physical interception of rain or dry fall-out (Russell, 1965; Martin, 1963, 1965) and uptake depending on soil chemistry (Shulz, 1965; Tamura, 1963, 1964, 1965) and on plant-soil relations (Menzel, 1965; Fredriksson *et al.*, 1961, and many other studies).

Food chain transfers of fall-out to man have been emphasized not only by accumulation of ^{90}Sr and ^{131}I via milk, cattle and pastures (Comar, 1963). but recently by temporary high levels of ^{137}Cs in Lapplanders and Alaskan Eskimos (Svensson, and Liden 1965; Hanson and Palmer, 1965 respectively). In the Arctic, reindeer or caribou feed on lichen vegetation which has been very effective in intercepting fall-out (as well as its normal nutrients) from the atmosphere.

Simple "concentration factors" have been useful for summarizing transfers from one step (or compartment) to another. However, the limitations of monitoring approach (Auerbach, 1965) have tended to focus increasing interest on the quantitative models which treat income and loss rates explicitly (Olson, 1963*a*, 1963*b*, 1965; Martin, 1965), in terms of coefficients of transfer like those in matrix (1). By integrating the expected income and loss terms due to all significant transfer rates, it should be possible to predict the levels and changes of accumulation under specified conditions without waiting for some catastrophic accident to bring them about.

Fall-out problems have also stimulated the quantitative studies of larger-scale geochemical cycles. Many fall-out studies concern the transfer rates between different parts of the atmosphere. and from the atmosphere to different parts of the hydrosphere, lithosphere, and biosphere. On this scale, we should like to specify the probability for a given element or isotope in any of these "spheres" to move to the other "spheres". These probabilities, like those expressing movement within some local ecosystem, should be expressible in a matrix-like equation (1), and should control the changes summarized in equation (2).

TREE-TAGGING METHODS

Most ecosystem studies have been concerned with the intake of nuclides from the environment to organisms, or from one organism to another. By incorporating tracers within plants, it is also possible to show how promptly they are translocated between plant parts, and to measure the loss rates from the plants to the environment completing the local cycle of the elements.

Scaling-up plant tagging from small plants in the greenhouse or field to full-size trees involves several variations of technique. Fraser (1956, 1958) reviewed many findings as well as methods of tagging and monitoring trees. Holes drilled into the wood, and troughs constructed around the bole (Fraser and Mawson, 1953) have been useful in our own studies reported below.

The Mauget Feeder is an aluminium tube inserted by driving into the tree along with a nail, and attached to a small plastic reservoir by a rubber gasket. We have found it useful under favourable transpiration conditions, but the slow emptying under other conditions (Witherspoon, 1964) has the disadvantage of leaving isotopes exposed to possible disturbance by animals, unless the insertion is actually made in a taproot below ground, as proposed by Ealy (1957).

Postlethwait and Rogers (1958) used variations on the Fraser method, one including a tin can reservoir firmly sealed to one side of a tree, with sufficient depth of liquid so that cuts through the bark could be made under water, and another method using chisel cuts without bothering to maintain the water column in this way. Even with these breaks in the water column, and transverse cuts which severed half the vascular system at the point of injection ^{32}P moved around these cuts and up the trees, during June when transpiration conditions were otherwise favourable.

Other methods of getting the nuclides into trees (Tukey *et al.*, 1955) include foliar spraying and the wrapping of gauze around branches of trees. Single roots (Rubin and Moiseichenko, 1963) or cut branches were also effectively tagged by insertion into isotope solutions by Kuntz and Riker (1955). The latter authors and Bormann and Graham (1959) showed rapid translocation below ground between grafted root systems of different individuals of the same species, illustrating a physiological interdependence among "individuals" of the same community.

Using Bormann's method of application of nuclides on cut stumps, a brief study with Russel Hutnik in 1960 at Oak Ridge National Laboratory showed only sporadic transfers between root systems of loblolly pine (*Pinus taeda*). Yet there was conspicuous transfer of ^{86}Rb to deciduous shrubs (*Rhus copallina* and *Acer rubrum*), apparently by translocation across intimate contact of ungrafted roots which have grown together. Witherspoon (1964) reported transfer of ^{134}Cs from tagged white oak (*Q. alba*) sapling to seedlings of sourwood (*Oxydendron arboreum*), an Ericaceous tree which became as radioactive per unit weight as the donor oak. Woods and Brock (1964) have likewise shown transfer of ^{45}Ca and ^{32}P from red maple (*Acer rubrum*) to other species.

Garnaga (1955) measured the rapid uptake of both these nuclides into the canopy of apple trees during inflorescence. Picard *et al.* (1962) included not only ^{45}Ca and ^{32}P but also ^{59}Fe and ^{35}S in their studies of penetration and translocation in fruit trees, and leaching losses from trees (cf. Tukey and Amling, 1958).

In some of the following experiments, two or three radioactive isotopes were included in the same injection solution to show differential movement of elements up the trees, and out of the trees. One of the simplest methods of separating the counts from mixed isotopes was in the case of very short-lived ^{42}K (12.4 hour half-life) which practically disappeared after only one week, so that samples which were first counted for this nuclide could simply be counted again for measuring nuclides originally associated with it.

Measurement of other nuclides in mixtures (^{85}Sr and ^{45}Ca) was also accomplished, by adjusting liquid scintillation counter so that ^{45}Ca was measured only in the channel of lower radiation energy. The ^{85}Sr was detected in both channels and (with higher efficiency) by a solid scintillation crystal detector system. A solid crystal spectrometer, an automatic sample changer for 2.5 cm test tubes (Packard Auto-gamma) and a bulk counter (Packard Armac) for litter-sized samples have all been valuable for the experiments with gamma emitters in handling numerous small samples or large samples respectively.

OAK RIDGE RESULTS ON TREES

The methods described have been useful in comparing the mobility of several elements or element groups of the periodic table. Differences are consistent with expectations drawn from herbaceous plants, but are displayed in a striking manner by trees. Furthermore, the studies on oak saplings and a whole plot (20 × 25 metres) of tulip tree forest furnished unusual opportunities for interpreting the budgets of income and loss for an element (cesium) having important long-lived isotopes.

^{42}K, ^{85}Sr *and* ^{45}Ca *triple tag of flowering dogwood*

Tagging of three nuclides in a flowering dogwood tree (*Cornus florida*) at Oak Ridge National Laboratory is of methodological interest in furnishing a comparison of movement of three different elements introduced together as a "triple tag". The ^{42}K essentially served as a temporary tag for the dilute salt solution (0.1 N KCl, pH 5) in which ^{45}Ca and ^{85}Sr were also dissolved. Approximately 20 ml of mixture and 25 ml of rinse KCl were injected into the trunk 1 dm above the ground through a 1 cm tube, under pressure from a garden spray pump (Fig. 1). Geiger-Müller survey meters showed rapid upward movement of the radioactivity along the vascular system of the tree. The tagged "front" reached the tip of one tree fork (3 metres from source point) less than 5 hours after tagging at noon on a sunny spring day (4 May). Samples collected the same afternoon (Table 1) showed that most of this activity was due to the strong gamma radiation (1.6 Mev) of the ^{42}K.

TABLE 1. Gamma activity in dogwood injected with mixed isotopes, 4 May

	Distance from source (cm)	^{85}Sr dpm	^{42}K dpm
30 minutes after tagging:			
Lower trunk branches	60	140	33 994
Lower crown branches	130	0[1]	
Upper crown branches	266	0[1]	
5 hours after tagging:	115	0[1]	281
Branches from four forks	110	124	27 558
	140	11 237	430 562
	210	0[1]	2 844
Top of tree	330-480	0[1]	2 697
Selected top branchlet	480	0[1]	18 301
22 hours after tagging:			
Top of tree	330-480	0[1]	4 193
Selected top branchlet	480	0[1]	

Total activity in 0.1 N KCl (pH$_5$): ^{45}Ca 2.18 mc; ^{85}Sr 0.79 mc; ^{42}K 4.0 mc.

1. No activity detectable above background.

When the same samples were recounted a week later, after the short-lived ^{42}K had virtually disappeared by radioactive decay ^{85}Sr was found only in two of the four main forks of the tree, and was mainly concentrated in one of these—evidently the one whose xylem was most directly aligned with the point of inoculation. Potassium had evidently diffused laterally enough so that it was present (though in very different concentrations) in all four forks of the tree.

While potassium had moved all the way to the tree top (4.8 metres in less than 4.8 hours), ^{85}Sr was not

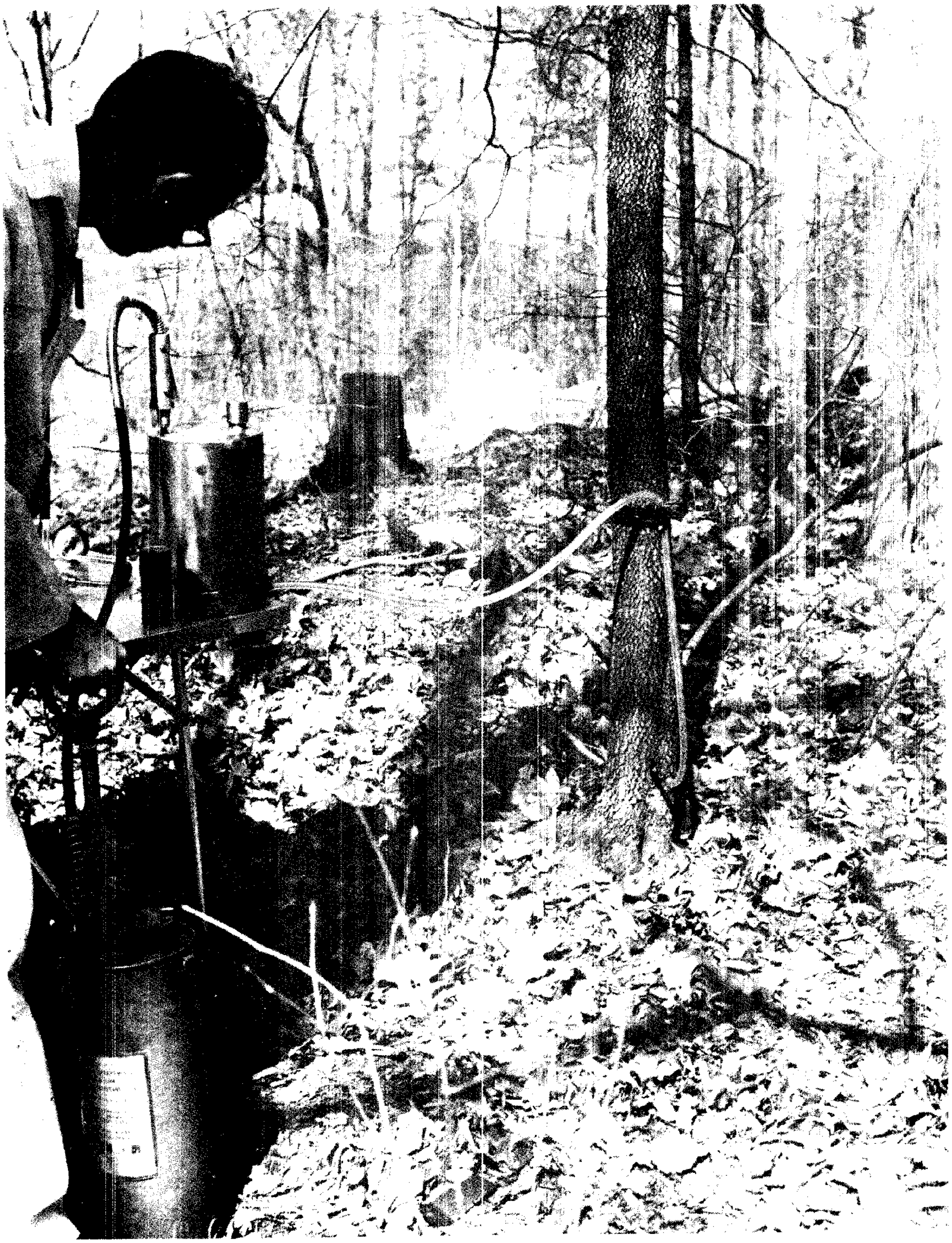


FIG. 1. A garden pressure pump pressure tank used to hasten movement of tracer mixture from tygon tubing into a pipe threaded in bole of flowering dogwood tree (*Cornus florida*).

even detectable there the next day, or for several weeks thereafter. We expected rapid movement of free alkali metal ions, as Fraser (1956) found with ^{86}Rb, and as was later found with cesium (see below). Evidently the alkaline earth ions were not moving as freely as the alkali metals, and this represents a general finding of other experiments. Exchange and dilution with stable Ca and Sr (e.g., in pectic substances and other sites in cell walls, cytoplasm, and perhaps oxalate crystals) could help explain their lag.

Plants, like animals, evidently can discriminate between Sr and Ca. The lag of ^{85}Sr was somewhat greater than that of ^{45}Ca, as these two alkaline earth ions continued to move up the trees during the rest of the growing season after the rapidly moving ^{42}K had disappeared (Table 2).

Table 2. Discrimination between ^{85}Sr and ^{45}Ca in flowering dogwood trees (*Cornus florida* L.)

Nuclide	Half-life	Input to tree bole (millicuries in tag) 4 May	Output into tree leaves (dpm per mg of leaves)[1] 2 July	26 August
	days			
^{85}Sr	55	0.79	57	208
^{45}Ca	155	2.18	374	1 080
Ratio ^{85}Sr/^{45}Ca		0.362	0.153	0.193

1. Composite samples corrected for decay.

The ratio of ^{85}Sr/^{45}Ca (corrected for decay) remained below that in the tracer solution during summer sampling periods, but was not as low in late summer as in early July. In spite of the differences shown here, the ratios are similar enough to indicate that Sr movement shows much in common with Ca in trees, and presumably after leaf fall as well.

Leaves from this and other trees (discussed by Olson and Crossley, 1963) were harvested at the end of the growing season. These leaves were used for studies of litter breakdown and succession of mites, using litter bag technique. Probabilities of loss from the litter bags (per day) for ^{85}Sr averaged $p = 0.00137$ and 0.00175 in pine and oak stands, and were not significantly different from the rates of leaf weight loss ($p = 0.00135$ and 0.00175 per day). Except for faster breakdown and release in early weeks in the field and slower rates in midwinter (Olson and Crossley, 1963, Fig. 7), the fraction remaining in litter can be approximated fairly well by negative exponential decay (Olson, 1963*b*) while the lost material would be accumulating in soil below the litter bag:

$$\text{Fraction remaining} = e^{-pt} \tag{3}$$

$$\text{Accumulation in soil} = 1 - e^{-pt} \tag{4}$$

^{134}Cs *(and* ^{42}K*) in White Oak*

In another double tag experiment (using the Mauget feeder method) with ^{134}Cs and ^{42}K, Witherspoon (1964) showed that both elements could be detected in rainfall

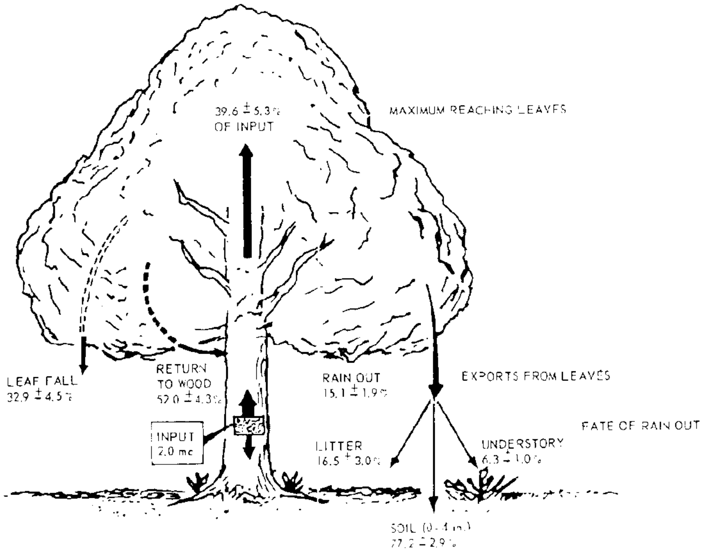


Fig. 2. Redistribution of ^{134}Cs in white oak (*Quercus alba*) based on an average of 12 trees for two years (1960 only for soil) (from Witherspoon, 1964).

which leached through the canopies of small white oak trees (*Quercus alba* L.) on the night following tagging. The potassium was generally similar to cesium in its distribution, but leached even more readily. It also tended to concentrate in buds, and perhaps, by inference, in other meristems.

Whereas ^{42}K is too short-lived (and ^{40}K too expensive) for following seasonal changes, the half-lives of ^{134}Cs (2.07 years) and ^{137}Cs (about 30 years) are ideally suited for longer-term experiments on the pathways and general rates of alkali metals through the ecosystem after ions leave the foliage (Figs. 2-7).

In *Quercus*, and later also in *Liriodendron*, foliage concentrations of cesium reach a maximum in June, and decrease throughout the summer. The average of 12 oaks in each of two years showed nearly 40 per cent of the injected ^{134}Cs at the time of maximum activity (in June). The decrease was considerably greater than that actually accounted for by rain leaching and leaf falls. By subtraction, half of the maximum cesium foliage content is evidently withdrawn into woody parts of the trees during the summer (Fig. 2). If activity in the surface decimetre of soil, and that in litter mat and understorey, are interpreted as due to rain-out from the canopy, this totals 15 per cent of the canopy maximum (of which only 6 per cent was retained in the understorey, 16 per cent in the litter layer and 77 per cent in the soil.) In the first year, 33 per cent of the maximum foliage content reached the surface in leaf fall, and furnished a new pulse of cesium activity at the ground surface, which increased the soil activity in the second year.

Transfers of ^{137}Cs *in a tulip tree forest*

After Witherspoon's experiment on white oak, several of us at Oak Ridge National Laboratory were interested in finding how the tagging of all the dominant trees in a forest would be followed by transfers to other vegetation, to soil, and to the animals and micro-organisms of a whole ecosystem. Our choice of study area was a nearly pure stand of tulip tree or yellow poplar (*Liriodendron tulipifera* L.), a member of the Magnolia family which is one of the most important species, ecologically and economically, in North America's Eastern Deciduous Forest. Our choice of methodology (described in detail by Auerbach, Olson and Waller, 1964) was an adaptation of Fraser's 1953 trough method (Figs. 3*a* and 3*b*). Thirty-five trees (from 37 cm down to 4 cm diameter at 1.37 m above ground) were tagged, with amounts of isotope ranging from 94.2 down to 0.4 millicuries, in proportion to the total tree biomass estimates derived from previous production studies which weighed trees in the same vicinity.

Instead of ^{134}Cs which has a 2.07-year half-life we used ^{137}Cs which has a 30.15-year half-life and which will be readily detectable a century or more from now. A total of almost 0.5 curie of this isotope was used; the area is completely fenced from the public and is located in a situation where there is no external drainage (Olson, 1965).

Uptake of water from the trough was so rapid that one man had to pour water into the reservoir while I made chisel cuts at 5 cm intervals around the tree, and while others were removing the vial of $^{137}CsCl_2$ from its shield, diluting it in water, and pouring it into the trough. More water was poured into the trough to help wash the tag into the tree, before the open trough was sealed over. On top of the trough, a new trough was constructed so that samples of stem flow water could be collected later, and compared with samples of rainfall that had dripped through the tree canopy and leached cesium and other elements from it. Detailed results are explained in other papers, so I select here only a few key points to illustrate how several physiological and environmental processes quickly change the cesium budget of this ecosystem.

Upward translocation of radioactivity was rapid, so that foliage samples, though initially quite variable (Olson, 1965) averaged between 1.2 and 1.3 microcuries per gramme of dry leaf tissue, during June 1962, only two to four weeks after the tagging of 20-24 May (Fig. 4). Canopy concentrations decreased steadily throughout the summer. The losses were considerably greater than could be accounted for by the measured rain-out, or by premature leaf fall or insect feeding. As in the case of oak, there was apparently a very important withdrawal of Cs from foliage to branches, the tree bole and roots. About half the maximum content of cesium was lost before late September and more has occurred during leaf senescence (Fig. 5).

Independent evidence of the rapid movement of cesium down to even the finest of roots was found in early soil sampling (Waller and Olson, 1964; Olson, 1965; Witkamp and Frank, 1964). By October, about 207 millicuries, almost half of that introduced in the trees in May, was found in the surface 30 cm of soil. Most of this was located in roots, and most of the activity that had been released already to the soil presumably came from excretion, leaching or death of roots. Our accounting for rain-out and leaf drop could explain only a small fraction of the total which was represented in soil and roots. We estimate only about 4 per cent of the cesium leached by the overstorey was intercepted by the ground cover vegetation. In the first year, and even through the second year, ground vegetation apparently got relatively little of its radioactivity from the soil.

MODEL EVALUATION

To account for the net changes in cesium activity in parts of the environment requires allowance for simultaneous incomes and losses for various parts of the ecosystem (Table 3). These changes in turn depend on the proportions (or probabilities) of transfer between

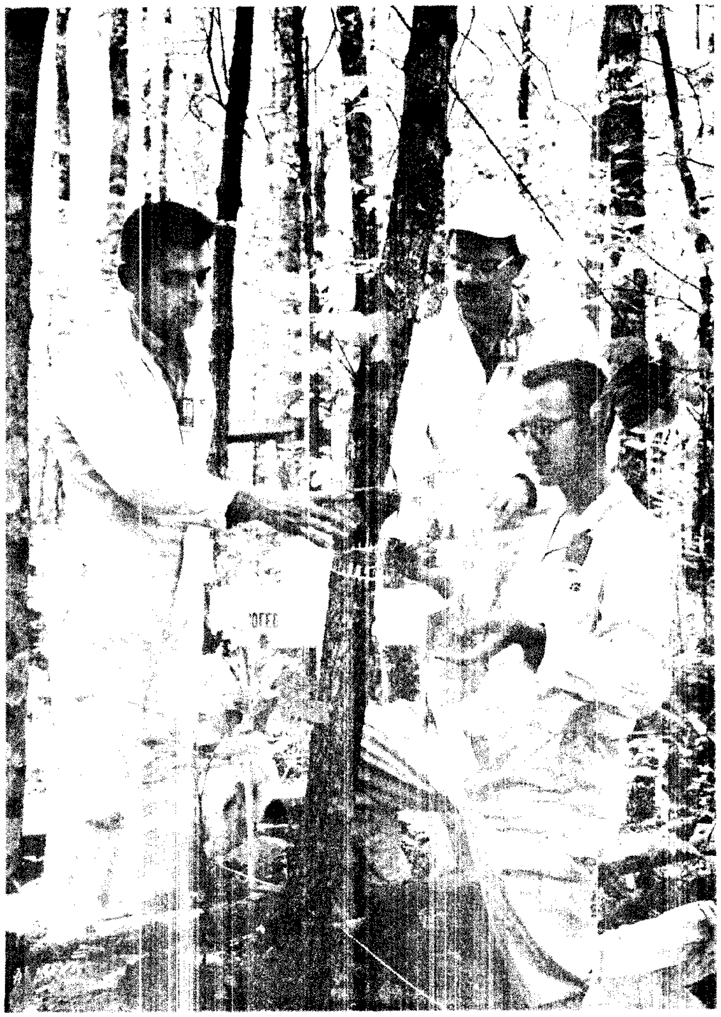


FIG. 3*a* (*above*) and 3*b* (*right*). Preparation and use of troughs for tagging a tulip tree (*Liriodendron tulipifera*) forest.

3*a*. Malleable perma-gum pipe-sealing compound was formed into a trough around plastic tape over smoothed bark, and then supported by aluminium foil and wire.

3*b*. Water was poured into trough while chisel cuts were being made every 5 cm around the tree, to keep the xylem from being blocked by air until the ^{137}Cs was removed from the lead shield and poured in, and followed by rinse water.

those compartments which are connected to one another by the relations shown in expression (1) in the model described earlier. Some of these transfers (like the amounts measured in rain-out, small slabs of litter, and vegetation) were estimated fairly directly from field measurements. Without destructive sampling of the forest stand itself, it was necessary to estimate certain transfers between the trough, the wood, foliage, bark and roots indirectly, by showing what values could be assumed in order to get patterns of change through time like those which were actually observed.

Simulation methods described elsewhere (Olson, 1965) were used to generate curves for the amounts of radio cesium in various compartments of the forest ecosystem (Fig. 6). Essentially, these curves are created in a series of daily steps, in which the amounts of material in compartment *j* today are redistributed to the other compartments (at the rates given in Table 3). The state of the ecosystem tomorrow was computed as the sum of what was left in it after losses to other parts were subtracted, and what was added by input from other compartments, as summarized in equation (2). The actual calculations were done assuming that transfers were deterministic, but the model, in principle, allows that an element of chance variation could be added to furnish the kinds of fluctuations sometimes observed in nature.

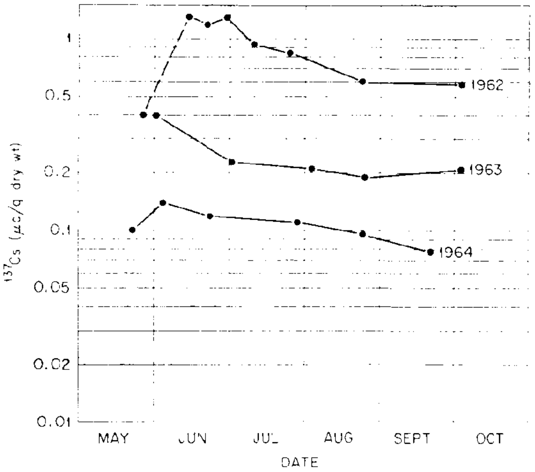
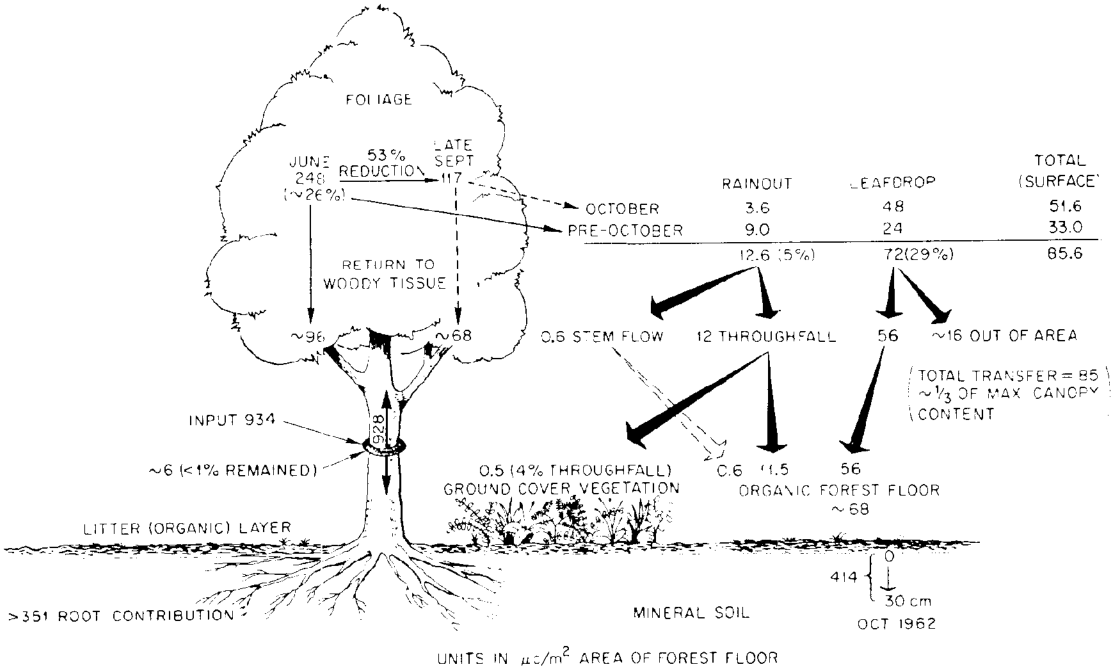


FIG. 4. Rapid initial rise in foliage activity (dashed line) followed by diminished ^{137}Cs content throughout the summers of 1962, 1963, and 1964.



	RAINOUT	LEAFDROP	TOTAL (SURFACE)
OCTOBER	3.6	48	51.6
PRE-OCTOBER	9.0	24	33.0
	12.6 (5%)	72(29%)	85.6

FIG. 5. Summary of movement of ^{137}Cs from *Liriodendron* tree canopy in 1962, and income to the soil by rain, falling leaves, and especially by downward movement through the bole to fine roots, which in turn release Cs to the soil (Waller and Olson).

Table 3. Constant coefficient model for ^{137}Cesium transfer during first summer in *Liriodendron* forest: proportion P_{jk} (per day) of cesium remaining in part j that moves to part k

j (compartment of origin)	k (receiving compartment) 1 "Source"	 2 Leaves	 3 Bark	 4 Roots	 5 Undercover	 6 Littermat	 7 Soil
1 "Source"	0.964	0.028[1]	0.008[1]				
2 Leaves		0.9556	0.044[1]		0.00005[2]	0.00035[3]	
3 Bark	0.005[1]	0.005[1]	0.975	0.015[4]			
4 Roots			0.007[1]	0.99			0.003[4]
5 Undercover					0.98	0.02	
6 Littermat						0.98	0.02[4]
7 Soil				0.0001	0.00001		0.99989

1. Adjusted primarily for fitting increase and decrease in foliage activity.
2. Derived from undercover sampling in August.
3. Derived from July sampling, small boxes, and leaf fall.
4. Adjusted to make soil samples (July and October) account for appropriate fractions of theoretical soil and root activity. Diagonal terms are adjusted to equal (1 — non-diagonal terms in same row), i.e., the proportions assumed to remain in the same compartments each day.

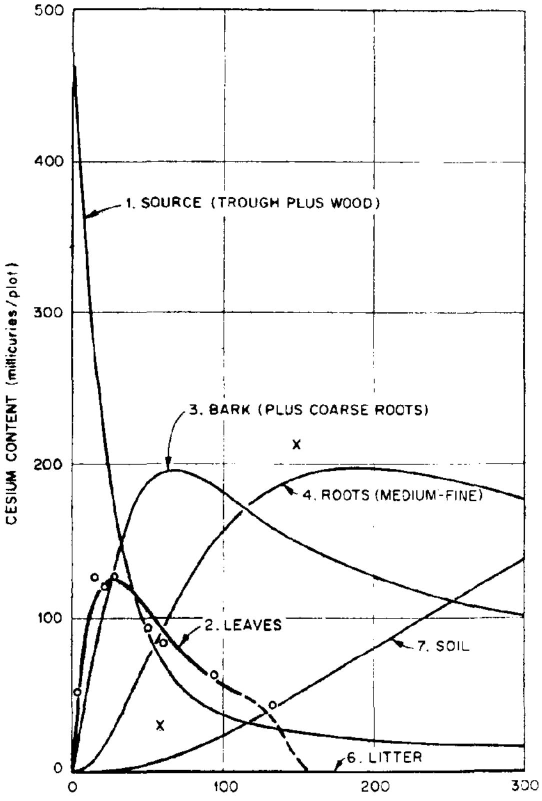


Fig. 6. Computer simulation of ^{137}Cs movement out of tree wood (compartment No. 1) to foliage (No. 2), bark and roots (Nos. 3 and 4) litter (No. 6) and soil (No. 7), assuming constant coefficients given in Table 3 (Olson, 1965).

Clearly the amounts of ^{137}Cs in the vicinity of the trough and also throughout the rest of the wood of the trees had to decrease quickly in order to account for increases in the rest of the tree. In foliage, radioactivity first increased while translocation from the xylem exceeded leaching and return translocation to the stems (presumably mostly in phloem). But soon these losses exceeded the rate of intake, explaining why the foliage radioactivity decreased as we noted before.

Autoradiograms of increment borings, and biochemical studies by Brown (1963), showed that highest concentrations of cesium occurred in the phloem and cortex regions of bark. Most cesium remains associated with cell fluids rather than any specific molecular sites in the tissue. It is but a minor impurity in the usual osmotic solution of the cells.

High rates of transfer like those assumed in Table 4 were required in order to create the increase in activity that was found in medium to fine roots. A release from the roots in turn, of approximately 0.3 per cent per day, could account for the radioactivity in the soil, which is discussed in further detail elsewhere (Waller and Olson, 1964). The first order approximation model assumed here (discussed by Olson, 1965) made no provision for seasonal trends in the transfer proportions of Table 3, and hence no allowance for the obvious decrease in the foliage activity and the corresponding increase in litter radioactivity in the autumn due to leaf fall (dashed lines of Fig. 4).

Work has proceeded on the sampling of the forest in later years. The distribution in bark and wood at various levels of the tree had fitted into a regular pattern by the end of the first winter. A series of increment borings by Waller in 1963 and non-destructive measurements of cesium redistribution by glass rod dosimeters by Witherspoon agreed in showing an abrupt decrease in the roots in late March as the sap was

TABLE 4. Contrasts in undercover radioactivity due to foliar absorption versus root uptake (August)

Ground cover vegetation	Sample plant mass (g/m^2)		Plant concentration ^{137}Cs(μc/g × 10^{-2})		Ratio plant soil		Sprayed[3]
	1962	1963	1962	1963	1962[1]	1963[2]	
Christmas fern (*Polystichum acrostichoides*)	28	23	5.62	0.88	76[1]	1.4	0.48
Hydrangea (*Hydrangea aborescens*)	39	16	5.55	0.64	75[1]	1.0	0.02
Virginia creeper (*Parthenocissus quinquefolia*)	4	4	9.13	0.34	124[1]	0.5	0.02
Other species	14	2	11.64	2.59	158[1]	4.1	0.05[4] 0.48[5]

1. Mean soil activity 0.08 × 10^{-2} μc/g × 10^{-2} due mainly to rainout from tagged overstorey.
2. Mean soil activity 0.64 × 10^{-2} μc/g × 10^{-2} due mainly to release from litter and roots.
3. Mean soil activity 16.2 × 10^{-2} μc/g × 10^{-2} sprayed directly on forest floor, 1 April 1965.
4. Indicates those species that had a minimal amount of direct foliar contamination when the radionuclide was applied.
5. Indicates plants that received direct contamination from spray application of this radionuclide. This includes early spring flowering plants (orchids, violets, etc.) or perennial plants that retain their foliage throughout most of the winter months.

beginning to rise, before foliage leafed out in April. The decrease in root activity was accompanied by a prompt increase of cesium content in the main bole, followed by a delayed increase in branches in the tree canopy.

Losses by leaching, leaf fall, and by root excretion continued in the second and third years, following a seasonal pattern much like that of the first year. However, the net result of all these losses was a decrease in radioactivity of *Liriodendron* in 1963 to one-third of the level it showed in 1962. Another marked decrease was evident in 1964 (Fig. 4).

By blowing of leaves, radio cesium was also moving out of the tagged plot into surrounding forest (Fig. 7). Because of the topographic depression where the plot was located and the height of surrounding trees, the distance of dispersal was not as great as might have been expected under many other conditions. Neverthe-

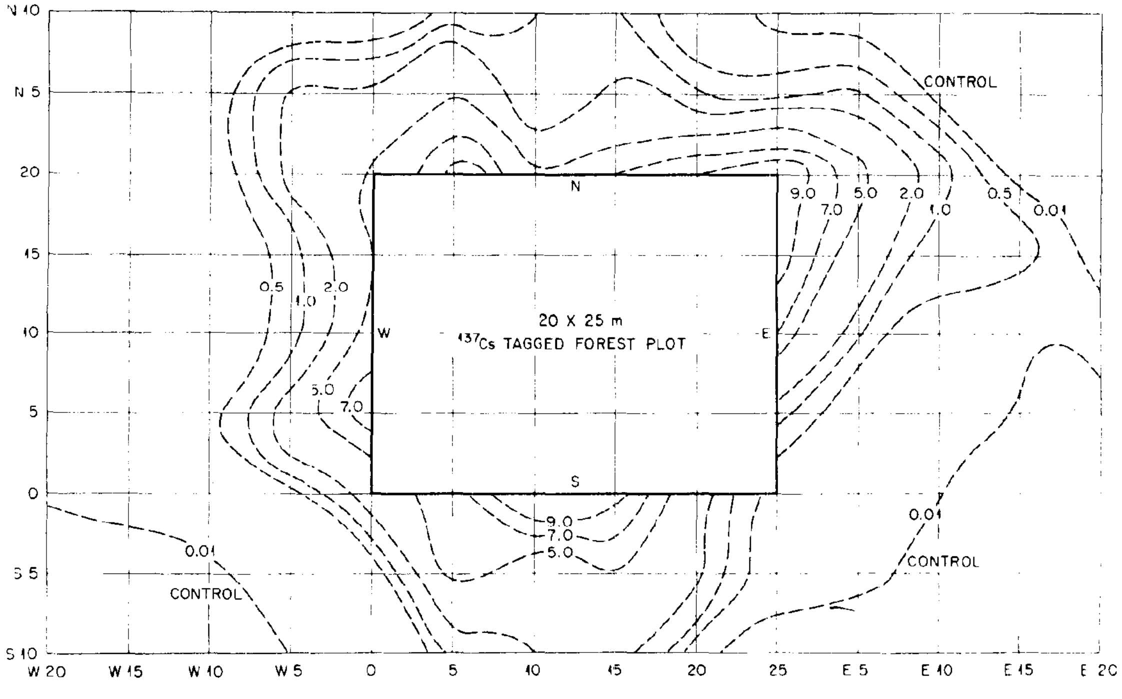


FIG. 7. Atmospheric dispersal of tagged *Liriodendron* leaves outside the 20 × 25 metre plot in 1963 (Olson and Waller).

less, it illustrates the general point that ecosystems are not closed systems (except for rare microcosms like those considered for aerospace vehicles). We should like to evaluate the proportions or probabilities of transfer between ecosystems as well as within ecosystems, by models like that of expressions (1) and (2).

ROLE OF TRACERS IN THE INTERNATIONAL BIOLOGICAL PROGRAMME

As the last introductory speaker of this symposium, I should add some final points to my opening general comments in relation to the International Biological Programme. If there is a unifying theme of the IBP, it concerns man's relations to the ecosystems which affect him and which he in turn is rapidly modifying. Radioactive isotopes and pesticides distributed around the world emphasize the transport between these ecosystems, and the cycling and accumulation in certain compartments of these ecosystems (United Nations, 1964; Udall *et al.*, 1964).

The preceding examples of tracer studies, and many others (cf. Makhonina *et al.*, 1961; Schultz and Klement, 1963; Hungate, 1965), provide only preliminary hints of the broad role of isotopes in evaluating the hazards of pollution and also in basic ecological research. Aquatic tracer studies are further developed than terrestrial ones but are beyond the scope of this symposium. The tagged vegetation is a starting point for continuing studies of secondary consumption and decomposition in the same tagged forest. Here Crossley (personal communication) has distinguished between those insect food chains of herbivores and predators which lead rather directly from food sources which became radioactive quickly and others which did not. Studies of feeding and elimination rates furnish a new basis for estimating secondary production in whole communities of arthropods, such as the cryptozoans which hasten the release of nutrients and isotopes from organic debris on the forest floor (Reichle and Crossley, 1965).

What trends might be predicted in the ecologist's uses of tracers? The emphasis of methodology and isolated case studies will presumably continue for a while because many new techniques and interpretations are still being tested. But there will presumably be a shift toward a balanced interpretation of new results in the context provided by many biological, physiochemical and mathematical approaches to single systems. The analysis of ecosystem components and variables, evident in so many parts of this first international symposium on ecosystems, will hopefully provide the foundations for more synthesis concerned with the organizing relations and processes in the world's major environments.

Radioactive isotopes are used most freely at laboratories which have major existing responsibilities concerning environmental radioactivity. However, the number of universities, colleges, and agricultural experiment stations with instrumentation and safety procedures for similar work probably will increase steadily. Where such stations serve as centres for IBP research, it should be feasible to study aspects of productivity budgets and processes which cannot be treated by the more widely used harvest methods and chemical analysis alone.

My emphasis on radioactive isotopes should not distract attention from the importance of stable isotopes. While there is no useful radionuclide of nitrogen, ^{15}N has long since proved its value in demonstrating the importance and rates of nitrogen fixation in many plant groups besides legumes (Bond, 1963). In a provocative paper Stevenson (1958) has considered broad possibilities of fixation in non-nodulated plants and even in leaves. Her paper is unusual in relating laboratory studies to the extensive literature on nitrogen budgets of soil and vegetation on a unit area basis. Jansson (1958) illustrates the great value of ^{15}N in the study of mineralization and denitrification. These presumably should be considered in close relation to fixation rates per unit of ground area, in interpreting the over-all nitrogen budget of an ecosystem.

Stable isotopes have the practical advantage of not disappearing during the course of a long-term ecological experiment, but the cost of enough tagged material for use of a field scale may be high. The need for a mass spectrometer may be as costly and demanding of specialized attention as the need for counting equipment needed for radionuclides. Yet these needs must be met somewhere in order to help interpret the budgets of nitrogen or mineral elements.

CONCLUDING REMARKS

Among the most fundamental parameters describing the maintenance and change in ecosystems are the proportions or probabilities of transfer (per unit time) of energy and elements from one component of the system to another: the matrix of (p_{jk}) summarized in expression (1). The net rate of change (if any) for a given component in a particuler compartment of the system is naturally equal to the sum of all income rates minus the sum of all loss rates.

When a certain amount of organic material, or tracer introduced in organic material, is traced from one point in the system, the amounts in that compartment decrease, in something like an exponential manner (equation 3; compartment 1 in Fig. 6) as transfers carry the material elsewhere. The amounts in other compartments increase until income is practically balanced by losses (equation 4; also the rising parts of curves 2, 3, and 4 in Fig. 6). If losses overtake income rates, amounts then remaining decline as the introduced material moves on into an environmental "sink" or is transferred across the arbitrary boundary of the local ecosystem into neighbouring environments.

Transfers within plants and from trees to forest ecosystems were illustrated by isotopes of major nutrient elements, and by trace amounts of other elements such as cesium which happens to be an important, long-lived radioactive contaminant of the environment. The transfers thus illustrated have an importance for the underlying theory of maintenance in ecosystems, which transcends the importance of the particular element or isotope which is selected for particular experimental study.

Some chemical groups of elements like cesium, potassium and rubidium apparently warrant the generalization that large-scale transfers may take place on a time scale of hours or days within natural and cultivated vegetation. Yet these alkali metals may be immobilized in soils, and may be slow to recycle through the plant-animal-microbe food chains. Strontium and calcium move less rapidly through plants and probably show a wide variation in rates of recycling in lime-rich and lime-poor ecosystems. The productivity of many ecosystems depends on an input of nitrogen from the atmosphere, from surrounding ecosystems, or from the fertilizer bag, and may be clarified by field tracer studies with the stable isotope ^{15}N.

Increasing uses of tracers can be made, measuring net transfers of elements, even without requiring a mathematical analysis of the kinetics of transfer. Kinetic models will be useful for interpreting productivity data, even without requiring isotope methods (Olson, 1964). In the long run, however, the combination of tracer methodology and mathematical models of income and loss should be especially helpful in deepening our understanding of productivity budgets and processes in the diverse ecosystems which constitute man's environment.

Résumé

Application de la technique des traceurs à l'étude des cycles biogéochimiques (J. S. Olson)

Il est nécessaire de connaître la circulation des éléments nutritifs au sein de l'écosystème pour comprendre les liens existant entre son budget énergétique et les processus physiologiques dont il est le siège. La vitesse de circulation et la quantité de ces éléments transportés au travers de l'écosystème (végétaux, animaux et milieu), peuvent être étudiées au moyen d'isotopes.

Des expériences réalisées avec ^{45}Ca, ^{85}Sr, ^{90}Sr, ^{106}Rb. ^{32}B, ^{60}Co, ^{105}Ru et d'autres radio-éléments font apparaître de grandes différences entre les groupes d'éléments qui transitent dans les végétaux ou sont évacués par les *feuilles* ou les débris végétaux. ^{137}Cs et ^{134}Cs offrent un intérêt particulier parce qu'ils assurent une contamination radio-active de longue durée et qu'ils nous aident à comprendre les cycles et épicycles lents aussi bien que rapides des ions dans la nature.

C'est ainsi qu'au Tennessee, après avoir marqué des troncs d'arbre (*Quercus* et *Liriodendron*), on constate une ascension rapide de Cs et K vers le feuillage, au printemps. La concentration diminue ensuite en été et en automne du fait de transports vers la végétation du sous-bois, les débris végétaux et le sol (par suite du lessivage des feuilles par la pluie, de la consommation par les animaux, de la chute des débris végétaux, et particulièrement du transit de haut en bas vers les radicelles qui, en mourant, libèrent le Cs dans le sol).

De nouvelles méthodes permettant l'étude de la biomasse radiculaire en présence, de la production radiculaire, des cycles saisonniers de la reproduction secondaire le long des chaînes trophiques (insectes), des cycles des éléments nutritifs microbiens et des modèles mathématiques des écosystèmes, ont été développées par le groupe de recherches écologiques d'Oak Ridge.

Dans le cadre du Programme biologique international, on devrait tirer parti des traceurs stables (en particulier ^{15}N) en plus des radio-éléments pour étudier les questions auxquelles on ne peut pas donner une réponse satisfaisante par d'autres méthodes. Les paramètres propres à unifier l'ensemble du Programme seront les fractions de l'énergie et des éléments nutritifs qui entrent en jeu dans la production, c'est-à-dire les taux de gain ou de perte divisés par les quantités déjà accumulées dans les écosystèmes terrestres ou aquatiques, ou dans leurs divers compartiments.

Discussion

I. R. Cowan. Dr. Olson's use of matrix notation to describe the characteristics of the transfer in space of tagged chemicals is most elegant. I have two questions. First, can the method be used when the mechanism of transfer is primarily diffusion rather than convection? I have the impression that some of the assumptions made in the model are not valid in this case. Second, should the matrix, in principle, be made three-dimensional in order to include possible physico-chemical changes in the state of the tagged material in any one compartment? It seems possible that the values of the matrix elements at present depend on the position in the system at which the tagged material is entered, because this may influence the state in which the material is subsequently transported.

J. S. Olson. (1) Whether the mechanisms of movement are due to diffusion or mass transport, most compartment models express transfer rates or probabilities as fractions of concentrations in the source compartments. Where this concentration primarily controls the gradient between source and sink compartments, the approach seems rather analogous with that of diffusion which has been used so much by meteorologists at this meeting; perhaps there may sometimes be a direct proportionality p and K, although p or K or the relation between these could indeed be variables rather than absolute constants. Where there is a reverse flow, the process of equilibration depends essentially on the gradient and the opposing rates of transfer, as in the cases of diffusion and chemical equilibrium.

(2) A simpler means of distinguishing major chemical forms of a single element may be to increase the number of compartments n in our one-dimensional vector, and deal with a larger nxn matrix (still of two dimensions) whose additional transfer coefficients P_{jk} could indeed include rates of chemical reactions between certain compounds (say sub-compartments, within a single original compartment). This could be important for ^{14}C if a biochemical ecologist or physiologist followed the initial intake reported by Professor Ničiporovič, through the Calvin cycle and translocation steps, and transfers through the food chain and environment. Forms in pectic substances and several compounds are important for Ca. Brown's results showed that Cs in our trees was mostly in free ionic or very loosely bound association with organic materials, as this and the relatively quick mixing of Cs simplify the trial reported here. The possibility of adding an extra dimension for the state of the system (compartment X constituent matrix V) and for the transfer parameters (compartment X compartment by constituent) will be discussed in a future volume of *Advances in Ecological Research*; this furnishes at least a stimulating basis for making us think which parts of these arrays are accounted for.

J. L. Monteith. You haven't mentioned the possibility that tracer materials might be lost directly from leaf surfaces by atmospheric diffusion. If they are removed by rain, could they not be removed from your system by turbulence like spores and pollen. This might affect the fraction of material which you assume is returned to the wood during the season.

J. S. Olson. Total amounts in pollen have been estimated in years of unusually heavy flowering, and are not large by comparison with dispersal by leaves, even though the pollen could blow much further. Pollen and seed dispersal studies were made for *Tsuga canadensis* in Connecticut, and showed a pattern to be expected from wind dispersal from different directions. However, that work did not involve isotopes. In the humid non-windy climate of Tennessee, aphid exudates, animal faeces and other debris are produced from foliage but such materials are mostly carried downward by rain and gravity. Especially on deserts, coasts and many windy regions, explicit attention should indeed be given to air dispersal to the zone outside the local ecosystem, and the question of whether such exports are balanced by import from this surrounding zone.

P. Lossaint. Il y a sûrement parmi nous un certain nombre de personnes qui sont intéressées par l'utilisation des radio-isotopes. A ce sujet, je voudrais poser deux questions d'ordre pratique au D^r^ Olson : *a*) Quelles sont les précautions à prendre concernant la zone de protection autour de la parcelle d'essai ? *b*) Peut-on entreprendre ce genre d'expériences dans un laboratoire chimique normalement équipé ou est-il nécessaire de faire ces travaux à proximité d'un centre de recherches nucléaires ?

J. S. Olson. A map in *Health Physics*, Vol. 11, No. 12 (December 1965) shows the research area, inside a large chain-link exclusion fence which was already constructed around some air-shielded reactors of Oak Ridge National Laboratory. Since we used 467 millicuries of long-lived ^{137}Cs (30-year half-life), it saved us much delay to select this first major trial without waiting for fence construction or special approvals that would have been needed elsewhere. However, the inconvenience of adjusting our work to reactor operations, and the comparatively minor hazard actually shown by our results, suggest that future experiments of this type could preferably be made in less restricted locations. For very short-lived isotopes, like ^{42}K (12.4-hour half-life), there is also a practical advantage to being near the major source of isotopes so there is little loss during transportation. However, for nuclides of intermediate life (e.g., ^{32}P, ^{56}Rb, ^{45}Cs and others) there could be much more flexibility in the location of experiments. Wabash College and many small schools in America carry on experiments of value for research as well as education. Limited quantities of many nuclides (10 microcuries) are used in aquaria and pot experiments (i.e., miniature ecosystems) in American high schools, which can get financial aid for simple apparatus for class demonstrations and the science fair projects of imaginative students. There are advantages of close co-operation with nuclear centres, like those we have seen on our excursion to Riso on Sunday, during early use of isotope research techniques, but it should be possible to overcome difficulties with public relations to permit tracer work in many natural ecosystems.

F. L. MILTHORPE. I was very interested in your autoradiograph of vascular tissue. Does the high concentration of ^{134}Cs in the phloem indicate that there is a continuous recirculation of this element in the plant, as has been reported for ^{32}P?

J. S. OLSON. The relatively high concentration measured in the bark section of increment cores also suggests that phloem may be more important than xylem in the upward spring movement of Cs in the second and later years. In place of our trial model of a matrix with constant coefficients, which was intended only for application during the first growing season, it would be interesting to consider a model with a sinusoidal or other seasonal variations in upward and downward transfer proportions.

M. P. GOUNOT. Ne pensez-vous pas que votre modèle matriciel est fondamentalement semblable au modèle d'analyse d'*input-output* mis au point par Leontief en économie pour l'analyse des relations inter-industrielles. Si ce rapprochement est correct, il devrait alors être possible de profiter des nombreuses études faites sur la méthode d'*input-output*, en vue notamment de perfectionner le modèle mathématique utilisé par vous.

J. S. OLSON. Yes, the matrix of ecosystems is quite analogous with the input-output models of economic systems, and can be expressed in similar variations in form: continuous differential equations (Olson, 1964), deterministic equations, and stochastic Markov chains. The outputs of many *ecological* systems become inputs to *economic* systems, and fertilizers and other products furnished by the economy essentially feed back to agricultural ecosystems in man's effort to optimize productivity of the combined eco-system. I feel strongly that we ecologists and the new generation of students have much to learn from well-established and more recent contributions of mathematics and econometrics which have relevance for ecological and physiological models. My colleagues, Drs. Bernard Patten and George Van Dyne, and I, have attempted to integrate some of this material with basic ecology in a sequence of "Systems Ecology" courses at the University of Tennessee.

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RADIONUCLIDE TRACER MEASUREMENT OF FOOD WEB DIVERSITY IN NATURE[1]

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Determining the relationship, if any, between diversity and stability is one of the central problems of ecology. There is here no question about where to draw the line between "basic" and "applied" science; the maintenance of stable ecosystems is of interest to everyone. Definition and qualification of the concepts "stability" and "diversity" must accompany any serious study of the relationships between them.

General agreement can be reached on a workable definition of stability as the ability of an ecosystem to survive short-term changes in the physical or biotic environment. However, diversity is not such an easy quality to evaluate. Many investigators have considered the number of species to be an indication of the biological diversity of an ecosystem on the theory that the larger the number of species the greater are the potential adjustments that can occur in response to physical perturbations. Of the various species diversity indices proposed, those employing information theory (Margalef 1958, Patten 1962) offer the most promise. However, species diversity indices only reflect some maximum number of potential interactions; simply counting the number of species and individuals in the standing crop tells us nothing about which species and individuals are actually linked together in a functional manner. If as suggested by Connell and Orias (1964) and the data of Paine (1963), biological and not physical interactions constitute most of the dimensions of each species niche, then the number of trophic interactions between species of an ecosystem is the important parameter. Accordingly, the network arrangement of actual strands in the food web, as well as the theoretical maximum possible number, is what needs to be determined. Radionuclide tracers offer a powerful new tool for measurement of such food web diversity. In this note we present an example of a radionuclide tracer used to measure the diversity of the plant–primary consumer food web in a simple natural ecosystem.

The two dominant species of plant on a one-year old field in South Carolina were tagged with ^{32}P and its subsequent transfer to the primary consumer populations was measured. The two species of plant were camphorweed (*Heterotheca subaxillaris*) and horseweed (*Erigeron canadensis*). The methods and results of this investigation have been published (Wiegert, Odum and Schnell 1967). Using their "trophic transfer index" [(activity density in a consumer species/activity density in plant species) × total biomass of consumer] we have evaluated the relative importance of each possible trophic transfer pathway. We considered a trophic transfer index less than 1.0 equivalent to zero transfer. On this basis only 14 species of herbivorous insects plus aphids (the latter discussed in a separate paper by de la Cruz and Wiegert 1967) showed appreciable interaction with at least one of the two dominant plant species. The more than 80 other species or groups of herbivores collected from the quadrats were clearly not removing enough material from the plants to be considered as important members of the food web.

In Fig. 1 we have compared the lowest possible food chain diversity (model 1) both with the maximum diversity (model 2) and with the actual situation found in the South Carolina old field.

In hypothetical model 1, each species feeds on only one of the plants, resulting in the minimum of 15 interactions in the food web. In model 2 every species is shown feeding on both plants, resulting in 30 strands in the food web (disregarding possible predation on one herbivore species by another herbivore species). In the actual field case 5 species removed appreciable tracer only from camphorweed and 2 species only from horseweed. Eight species accumulated some ^{32}P in each quadrat and thereby were detected feeding on both species of plant. Thus, the

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Wiegert, R. G. and E. P. Odum. 1969. Radionuclide tracer measurement of food web diversity in nature. pp. 709-710. In: Symposium on Radioecology. (D. J. Nelson and F. C. Evans, eds.). U.S. AEC report CONF-670503.

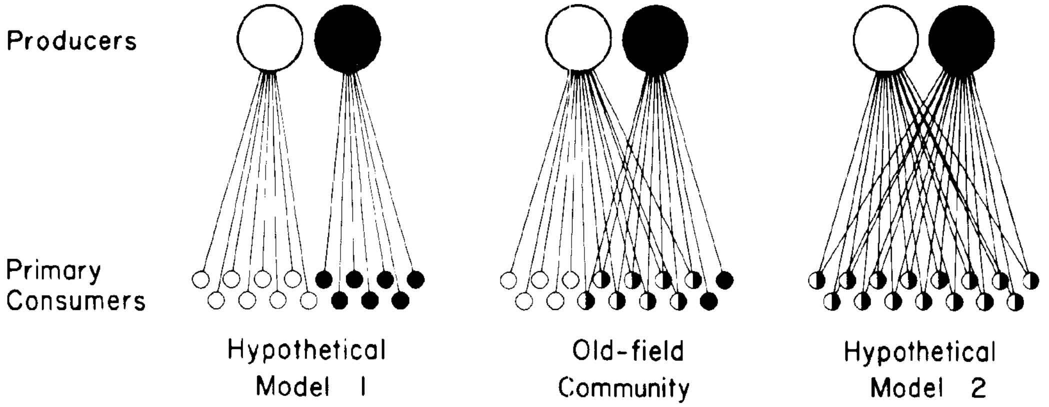

Fig. 1. The center diagram models the actual food web as mapped by ^{32}P tracer transfers for a 1-year old field community having 2 major plant dominants and 15 species of insects feeding on one or both plant species. The actual food chain network is intermediate in food chain diversity between the two hypothetical extremes shown.

actual number of pathways was 23 or 77% of the maximum (Fig. 1). However, no consideration is given to the relative amounts transferred from the different plant species by the different animal species. The trophic transfer index provides a means of quantitating transfers although the effects of species differences in rates of concentration and bioelimination of ^{32}P were not evaluated. For the 14 individual species discussed here (excluding aphids) the combined trophic transfer indices are 1542 for *Heterotheca* and only 190 for quadrats with tagged *Erigeron*. Because all consumer species were present in approximately the same relative density on both quadrats, this almost tenfold difference in radionuclide transfer reflects a large difference in the grazing pressure exerted on the two different species of primary producer. In this case the radionuclide tracer experiment revealed that only a few of the numerous insect species present in the community were closely linked to the dominant plants as consumers, and that the diversity and intensity of food chains was much greater with respect to one plant than to the other.

We feel that radionuclide tracers can simultaneously serve to identify the actual, as opposed to the merely possible trophic interactions, and tell us something about the quantitative importance of a given pathway. One can then deal with diversity in terms of network variables rather than merely in terms of number of species and individuals present. The possible refinements and variations of this method are only beginning to be realized. One could, for example, apply this to delineating food chains at the primary consumer–secondary consumer level by tagging insects instead of plants. Rates of uptake and bioelimination of the radionuclide during feeding by the different species must be determined, of course, before tracer transfer can be equated with energy flow. Eventually, it should be possible to determine the food web diversity for an entire community.

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IRRADIATION OF NATURAL VEGETATION

AN EXPERIMENTAL FACILITY, PROCEDURES AND DOSIMETRY

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Abstract—A portable 9200-c ^{137}Cs radiation source is described which meets the requirements for acute and chronic irradiation of natural plant and animal communities.

Irradiation of old field and forest communities has provided an opportunity to test experimental procedures and to compare dose rate distribution in two contrasting ecological systems.

Results indicate that in an ecologically and structurally complex community, such as a forest, the pattern of the gamma field is less predictable and more variable along both horizontal and vertical transects than in a less complex system, such as an old field.

Although the type of vegetation may greatly influence exposure rates within a short distance of a strong gamma source, at distances beyond 100 m exposure rates are little affected by the type of vegetation through which the radiation has passed.

Exposure of glass rod dosimeters to sunlight during irradiation resulted in a 24 per cent loss of fluorescence. Dose estimates were corrected accordingly.

I. INTRODUCTION

INVESTIGATIONS of the effects of ionizing radiations upon a variety of plant communities require: (1) a radiation source which is of sufficient strength to irradiate statistically adequate population samples within operationally feasible time limits; (2) a portable facility which can be placed in a variety of natural plant communities; (3) operational procedures which insure operator safety and which also minimize disturbance to the system under investigation; and (4) a dosimetry system which provides exposure rates and total exposure doses for a variety of biologically important microhabitats along vertical and horizontal gradients. Previous studies of radiation effects upon natural vegetation[1–6] have been conducted in fixed radiation fields where replication was difficult and where the vegetation was limited to a single community type or to transplanted segments of other communities. While a fixed facility provides extremely useful information, a portable source permits greater flexibility of experiments. The objective of this paper is to report on the use of a portable radiation source in a pine plantation and in an old field on the Savannah River Plant, and to compare the dosimetry of the two communities.

II. OPERATION OF THE RADIATION FACILITY

A. *The irradiator*

A brief description of the portable radiation source is included to clarify operational procedures and dosimetry. The source consists of 9200 c of ^{137}Cs in a stainless steel capsule. The capsule is centrally located in a 1500-lb lead cask (Fig. 1) which provides at least 5 in. of shielding in all directions. Two overlapping lead doors comprising the front of the irradiator are opened manually by rotating steel shafts which are connected to gear boxes. The long steel shafts extend behind the irradiator and through a concrete wall, which shields the operator. The doors open 45° in each direction.

McCormick, J. F. and F. B. Golley. 1966. Irradiation of natural vegetation. An experimental facility, procedures and dosimetry. Health Physics 12(10):1467-1474.

Additional safety features and alternate operational procedures have been included in case the gears jam or the doors fail to close.

B. *Operational procedures*

At the Savannah River Ecology Laboratory the portable irradiator is customarily kept in the Radiation Experiment Field which is a $1\frac{1}{2}$-acre old field surrounded by 8-ft high earthen bunkers and a 5-ft fence. A concrete wall, 16 in. thick and 8 ft tall, behind the gamma source reduces backscatter into the control house. The procedures for opening or closing the source are similar whether the irradiator is used in the permanent radiation experiment field or when it is used as a portable facility in natural areas.

When the source is to be moved from the permanent field, the irradiator is closed and chains are padlocked around the doors before shipment by truck (Fig. 2). Upon delivery to a natural area the irradiator may be moved into place by an overhead crane located behind the study area so as not to disturb the vegetation (Fig. 2). A tent is used as a radiation operations office, which houses necessary instrumentation. Power, if required is supplied by a portable generator (Fig. 2). Concrete blocks are used to construct a wall comparable to the one used in the radiation experiment field behind the source.

In the field experiment described here, access into the forest was restricted by (1) blockades and signs across local access roads, (2) a standard radiation danger nylon rope fence around the area receiving 50 mr/hr or more, (3) a 4-ft chicken wire fence around areas receiving more than 1 R/hr and (4) a 30-ft observation tower where an attendant on duty at all times, equipped with loud speaker and light, could warn any unsuspecting visitors.

After opening the irradiator from behind the temporary concrete wall the operator promptly retreated to an area receiving 5 mr/hr or less. The study area was not re-entered until the exposure period was terminated. Immediately behind the concrete wall the operator was exposed to a dose rate of 100 mr/hr. Since opening and closing the irradiator requires less than 5 min, total exposure doses were below 10 mr.

During the course of the investigation the attendant made a check of the perimeter at the 1 mr/hr zone for signs of entry. Savannah River Plant Patrol also made 2-hr checks at the radiation site. The field experiment was continued for 200 hr.

III. DOSIMETRY

The two communities which were irradiated, a 12-yr old field within the radiation experiment field and a 8-yr old pine forest, differed in ecologically significant criteria such as species density, distribution and size class, and community diversity and stratification, which could be expected to influence the pattern of the gamma field by means of vegetation shielding. The old field vegetation consisted of scattered clumps of broomsedge (*Andropogon virginicus*), lespedeza (*Lespedeza cuneata*), dog fennel (*Eupatorium capillifolium*) and a variety of less abundant annuals. The pine forest was a plantation of slash pine (*Pinus elliottii*) and longleaf pine (*Pinus palustris*) with an undergrowth of trumpet vine (*Campsis radicans*).

Exposure rates in the old field were monitored by placing remote area ion chambers rated at 5 per cent accuracy and Toshiba Low Z phosphate glass rods (inside clear plastic vials with a wall 0.5 mm thick) with an accuracy of 5 per cent at 5-m intervals on nine radii within the 90° gamma field. At each location dosimeters and ion chambers were placed at ground level, 0.5 m, and at 1 m above the ground. In the pine forest glass rods (in clear plastic vials) were placed at 10-m intervals along each of the nine radii (0°, and 11°, 22°, 34° and 45° left and right of center). At these intervals one dosimeter was placed in the canopy of a tree (approximately 6 m), another at breast height (approximately 1 m) and a third at ground level. At less frequent intervals additional dosimeters were placed at breast height on the side of trees opposite from the source and at a depth of 0.25 m in the soil. Remote area ion chambers were used at the beginning of the forest experiment to determine exposure rates at a few selected sites. Glass rods remained in the forest throughout the 200-hr experiment.

Following the report of environmental influences upon fluorescence of Toshiba Low Z glass rods(7) three additional experiments were conducted to estimate the effects of the natural environment (sunlight and temperature) upon fluorescence of rods used in the forest study.

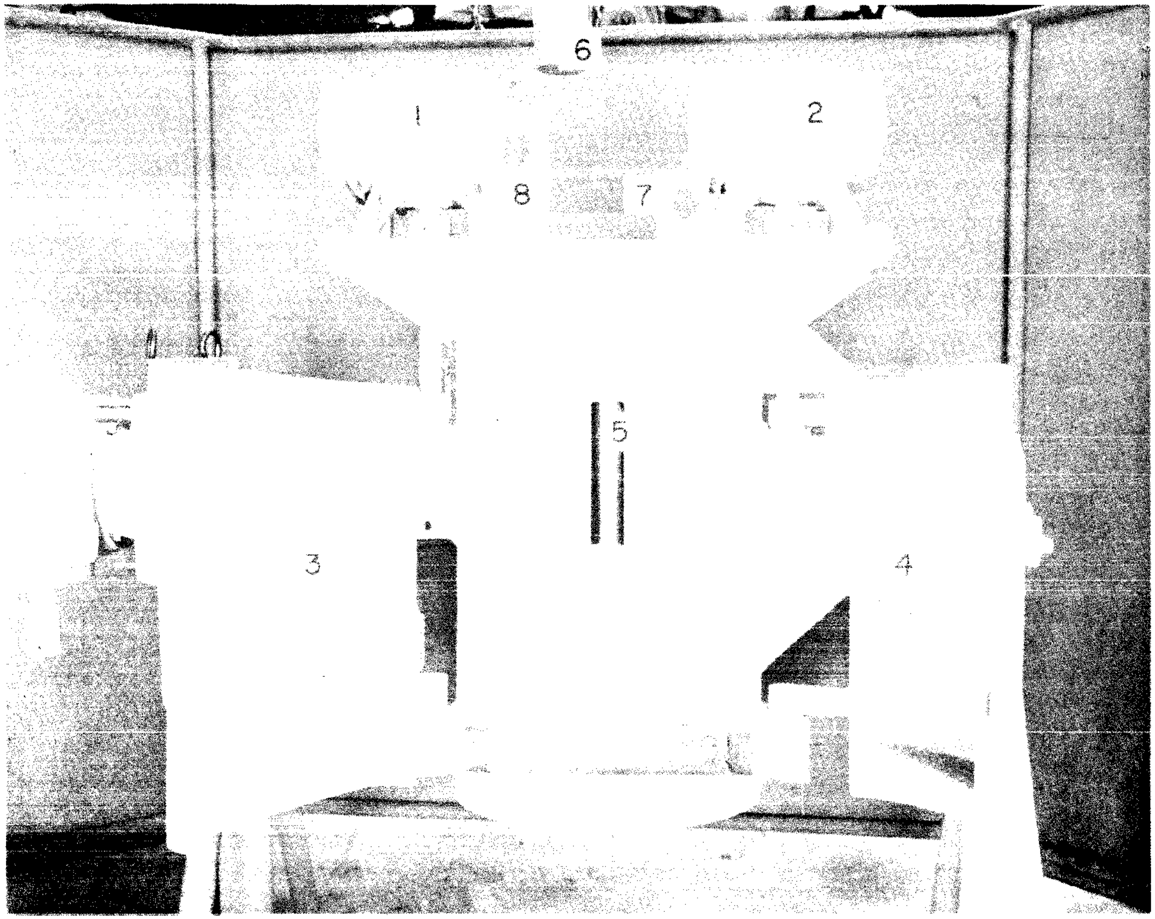

FIG. 1. A front view of the irradiator showing the gear boxes (1) and (2) which control the opening and closing of the inner (3) and outer doors (4) respectively.
The stainless stell capsule (5) containing 9200 c of ^{137}Cs is exposed by opening the doors or by removing the plug (6) from the top of the cask. The lifting bars (7) and (8) are used in transporting the 1500-lb cask.

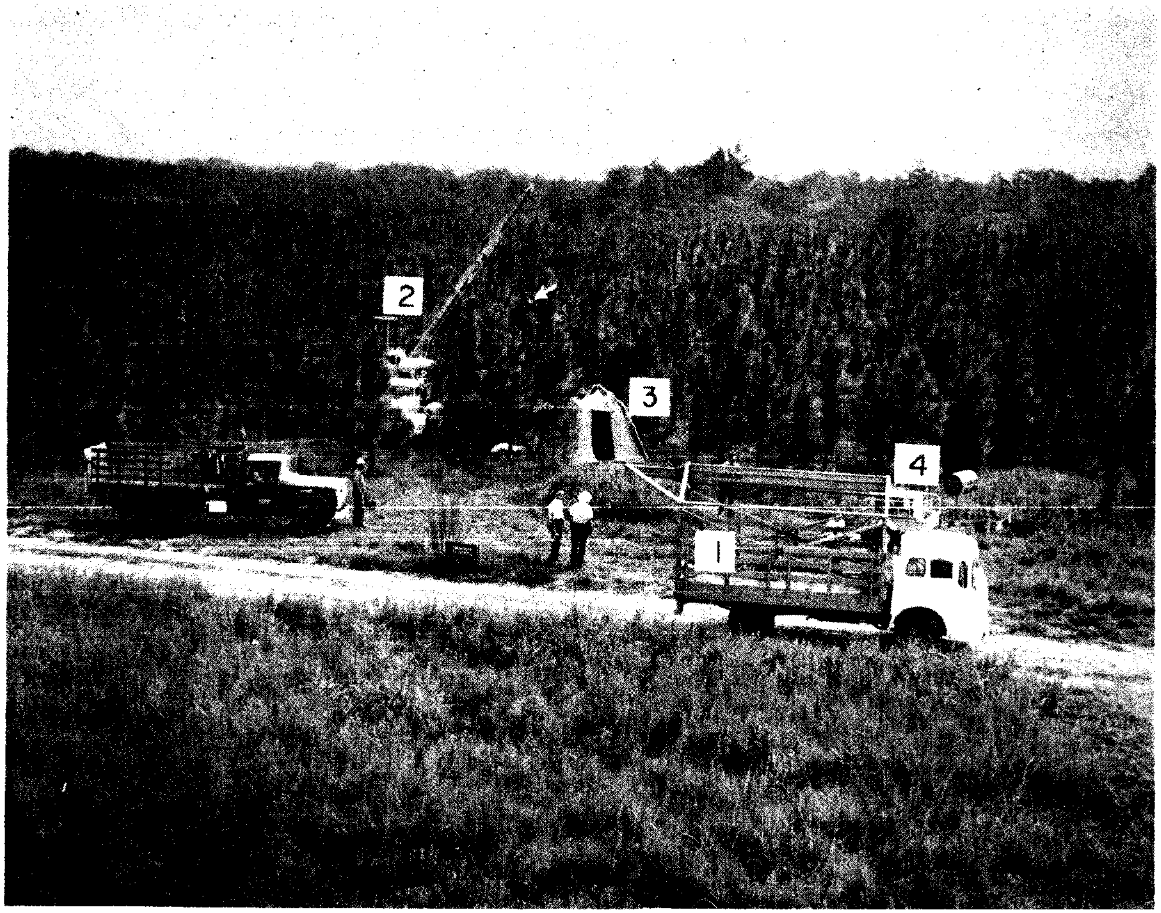

FIG. 2. Installation of the portable irradiator during the forest irradiation study. Facilities include (1) a truck to transport the irradiator, (2) a crane to place the irradiator in position without disturbing the vegetation, (3) a tent to shelter instruments and (4) a portable generator and fuel supply to provide power for instrumentation. The location of the irradiator is indicated by the arrow.

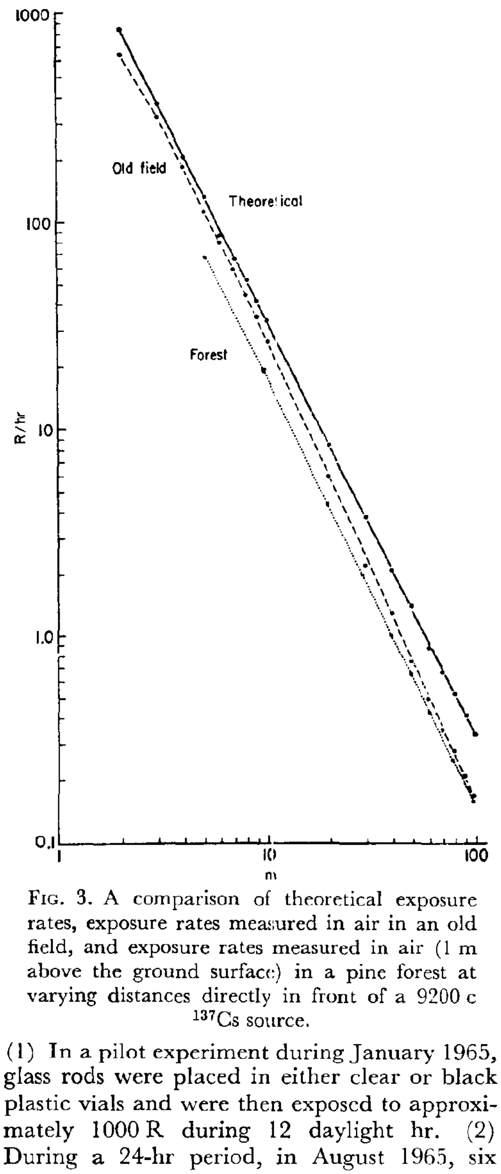

FIG. 3. A comparison of theoretical exposure rates, exposure rates measured in air in an old field, and exposure rates measured in air (1 m above the ground surface) in a pine forest at varying distances directly in front of a 9200 c ^{137}Cs source.

(1) In a pilot experiment during January 1965, glass rods were placed in either clear or black plastic vials and were then exposed to approximately 1000 R during 12 daylight hr. (2) During a 24-hr period, in August 1965, six glass rods were exposed to each of five radiation doses ranging from 900 to 2000 R. At each dose level two glass rods were placed in clear plastic vials, two in black vials, and two in black vials covered with aluminum foil to reduce suspected heat absorption. (3) In a final experiment, during August 1965, six glass rods received each of seven different doses ranging from 50 to 7000 R during a 200-hr exposure. Three of the six glass rods receiving a given dose were placed in a black plastic vial and the other three were placed in a clear plastic vial in order to test the effect of sunlight during irradiation. Following irradiation the fluorescence of all glass rods was read and exposure estimates were compared with those predicted on the basis of ion chamber measurements. Equal numbers of rods were then placed in clear and black vials. Half of the black vials were covered with aluminum foil to reduce suspected heat absorption. These vials were placed throughout the canopy and understory of the pine forest for 200 hr in order to test the effects of light and temperature upon pre-dosed rods. These rods were read again and results were compared with the previous readings in order to estimate changes in fluorescence due to canopy or understory environments. All rods were exposed to the same ^{137}Cs source used to irradiate the natural ecosystems and all vials had walls 0.5 mm thick.

IV. RESULTS

Results of the three experiments designed to determine the effects of environment upon fading of glass rod fluorescence demonstrated that: (1) following the 12-hr exposure of glass rods to sunlight during irradiation fading averaged 25 per cent; (2) during the 24-hr exposure fading averaged 20 per cent; and (3) during the 200-hr exposure fading averaged 28 per cent. No additional fading occurred when glass rods were placed in the forest canopy or understory for an additional 200 hr following irradiation. Glass rods in black vials with or without aluminum foil covers had the same fluorescence after exposure of the vials to sunlight. Thus, no temperature effect was observed. The average loss of fluorescence due to sunlight effect was 24 ± 4 per cent. Per cent fading was not related to total exposure dose. Subsequent data include corrections for the effects of sunlight on the dosimeters.

Comparisons of the theoretical exposure rates (according to the inverse square law), the exposure rates actually measured in air in the old field, and exposure rates measured in the pine forest along a transect straight ahead of the irradiator are illustrated in Fig. 3.

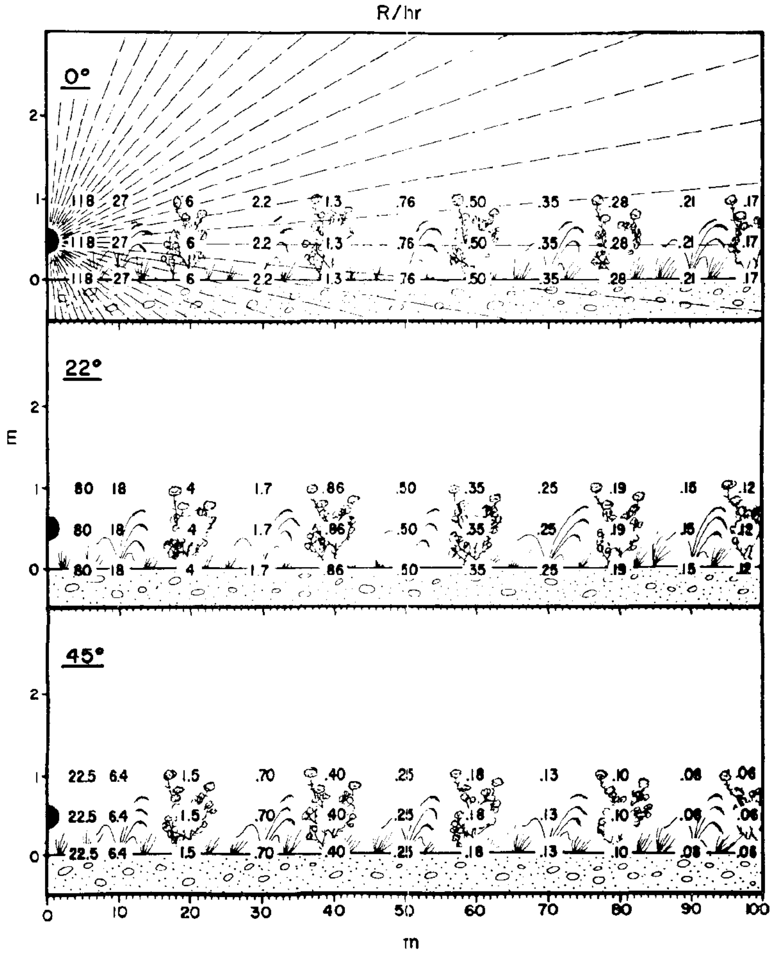

FIG. 4. Exposures rates (R/hr) in an old field exposed to 9200 c of ^{137}Cs. Exposure rates are illustrated for elevations of 1 m, 0.5 m and ground level along horizontal radii of 0°, 22° and 45° from the center of the gamma beam.

Differences between the theoretical and air exposure rates are primarily due to self absorption in the source with dimensions of 5.0 $\times$ 1.4 in., the shielding effect of the stainless steel capsule containing the ^{137}Cs, and absorption by the air. Deviations between exposure rates in the old field and the forest are primarily due to the shielding and scattering effects of the forest trees.

The gamma fields produced in the two contrasting plant communities are illustrated on three radii; (1) straight ahead, (2) 22° and (3) 45° to the side in Figs. 4 and 5. A summary of the results of the field irradiation experiments indicates that: (1) In the less stratified and structurally simple old-field exposure rates varied inversely with the distance from the source and the angle from the center of the beam. Vegetation did not produce a detectable vertical stratification of exposure rates nor did it produce unpredictable habitat deviations in exposure doses; (2) In the more complex forest

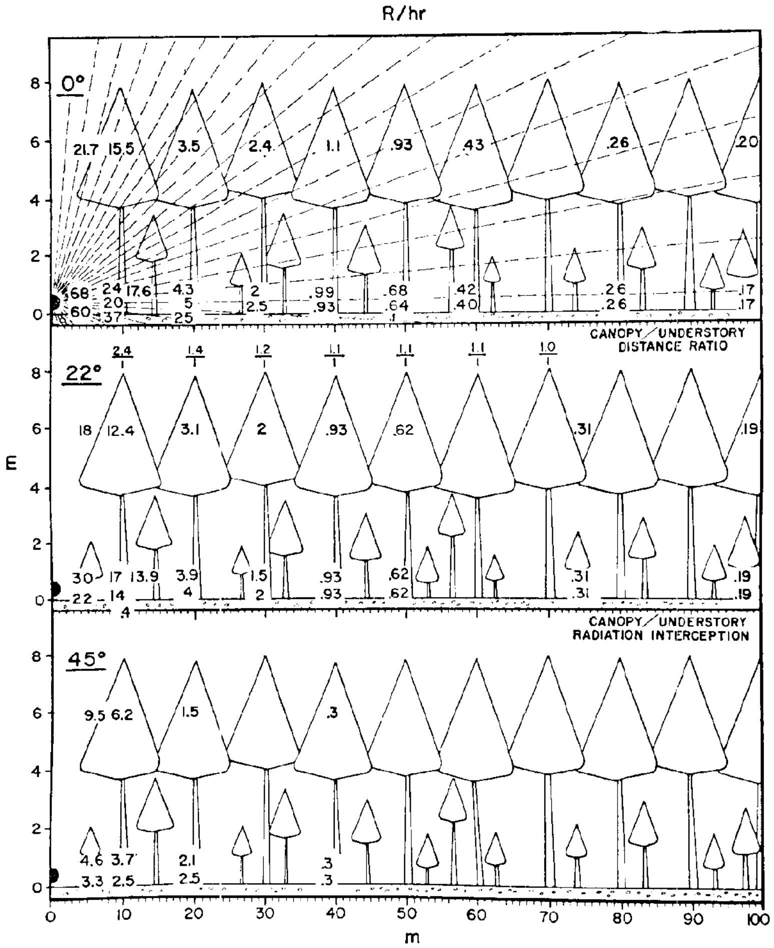

Fig. 5. Exposure rates (R/hr) throughout a pine forest exposed to a 9200 c ^{137}Cs irradiator. Exposure rates are illustrated for elevations of 6 m (canopy), 1 m (breast height) and ground level along horizontal radii of 0° (top), 22° (middle) and 45° (bottom) from the center of the gamma beam. Exposure rates are also illustrated for a soil depth of 0.25 m and for the side of trees away from the irradiator, at breast height, at 10 m, 20 m and 50 m along the 0° radius. The canopy/understory distance ratio, illustrated only in the middle frame, indicates the relative distance to the canopy compared to the distance to the understory at 10-m intervals. These ratios are identical along all radii.

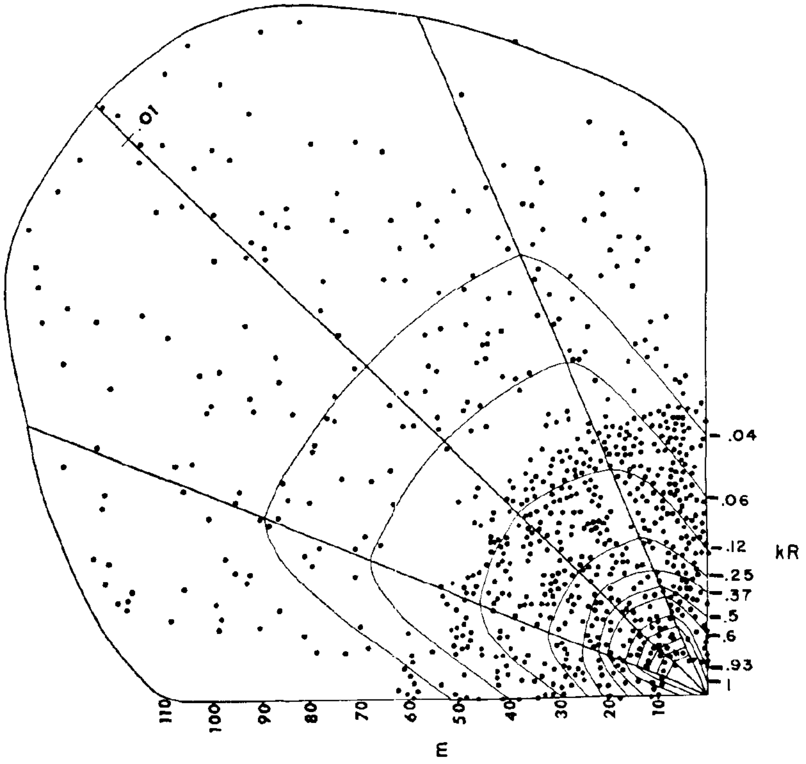

Fig. 6. Horseshoe shaped isodose lines produced during irradiation of the pine forest. The dots represent individual trees selected for studies of radiation effects. The first three isodose lines which were too close together to number represent 3.7 kR, 2.5 kR and 1.9 kR.

community vegetation shielding resulted in numerous irregularities in exposure dose. Of particular interest are the following observations which are shown in Fig. 5.

Within the first 20 m straight ahead and on the 22° radii the highest doses were recorded in the understory (breast height and ground level). Ground level doses were slightly lower than those at breast height at 10 m, probably due to the greater source to target distance along the downward angle. At 20 m distance the angle effect between ground surface and 1 m above ground level is reduced, and because of ground scatter, exposure rates at the soil surface exceeded those at breast height. At these distances the lowest exposure rates were observed in the forest canopy, which was the portion of each vertical transect most distant from the point source. The differences between distance from source to canopy and to understory vegetation are shown as ratios in Fig. 5. While these ratios are illustrated only in one plate of Fig. 5 (22°) for purposes of brevity, they are identical along all radii.

Along the 45° radii the highest exposure rates were received by the canopy rather than the understory. This may be due to: (1) the design of the irradiator which gives horseshoe-shaped isodose lines (Fig. 6); (2) the effect of the concrete block wall constructed along the 45° radii for about 6 ft beyond the cask; or (3) the presence of trees which were closer to the source along the 45° radii than along the 0° or 22° radii.

The highest exposure rates between 30 and 60 m straight ahead and at 30 m on the 22° radii were received in the canopy. There are several explanations for these results. First, at these distances the vertical angle from the source to the canopy is slight; the canopy/understory distance ratios ranged from 1.2/1 to 1.1/1. Second, an increased proportion of the path of canopy incident radiation is through the low density canopy, while understory incident radiation must pass through highly dense tree trunks. Third, the canopy probably receives more sky shine than the understory.

At distances beyond 60 m the vertical distribution of exposure rates is relatively uniform. As COWAN and MEINHOLD(2) point out, at these distances emissions from the ^{137}Cs source have scattered greatly. Also, the canopy/understory ratios reflecting distance from the source approach or equal unity at these distances.

One-fourth of a meter of soil reduced the exposure rate to approximately 2 per cent of that at 1 m height at distances of 10 m on the 0° and 22° radii. Soil exposure rates were reduced to 6 per cent of air dose rates at 20 m and 19 per cent of air exposure rates at 50 m on the 0° radius.

Individual tree trunks reduced exposure doses approximately 5 per cent at 10 m, 17 per cent at 20 m and 33 per cent at 50 m on the 0° radius.

V. DISCUSSION

Comparisons of the dosimetry data from the two contrasting ecological systems (Figs. 3, 4 and 5) indicates that exposure rates at comparable distances in each ecosystem become increasingly similar with increased distance from the source. At 100 m exposure rates are nearly identical in the old field and the forest. These data agree with those of COWAN and MEINHOLD(2) who reported that exposure rate–distance curves for gamma radiation passing through a wood and through air approach each other at great distances. They explain this in terms of the increased contribution of scattered radiation to the total dose with increased distance from the ^{137}Cs source. These data combined with those of COWAN and PLATT,(1) which indicate that terrain shielding may not provide anticipated protection due to high amounts of scattered radiation in valleys and ravines, suggest that topography and vegetation may have little influence upon gamma radiation exposure rates at distances beyond 100 m or so from a source of the type used here.

The experiments with the portable 9200-c ^{137}Cs irradiator demonstrate that natural ecosystems can be irradiated with safety to observers and other personnel. This study and others, point out that field irradiation experiments differ radically from theoretical models because of the complex geometries and scattering media which vary in the space and time of a single experiment. For these reasons it is essential to measure directly, rather than calculate, the doses to which individual organisms or populations are exposed during field experiments. The unpredictable and irregular distribution of exposure doses observed in the forest study should be considered along with other factors which affect the differential survival and growth of living organisms in irradiated ecosystems. It appears that the increased complexity of an ecological system, i.e. a forest vs. an old field, must be accompanied by a corresponding increase in complexity of the radiation dosimetry program.

Tests of the influence of environment on glass rod fluorescence indicate that doses are 24 ± 4 per cent higher than those calculated without considering the effect of sunlight on fluorescence. These results compare favorably with those reported by BLAYLOCK and WITHERSPOON.(7)

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PART V. NUCLEAR WAR, WASTE DISPOSAL AND PEACEFUL USES OF NUCLEAR ENERGY

Preface

Increasing populations throughout the world are resulting in increasing demands for energy as well as it appears resulting in increasing strife between nations. Nuclear weapons have the potential for enormous destruction of man and his environment and nuclear power reactors appear to many to be the answer to our energy needs.

Regardless of whether nuclear energy is used for destructive or constructive purposes ecologists, as well as many other persons, are concerned with ecological consequences of the nuclear age. Possibility of nuclear war has raised the spector of destruction of our environment by means of blast, fire and radiation damage. Of primary concern is whether or not the various ecosystems throughout the world are capable of self repair, and the time span and successional patterns involved. It is rather obvious that survival of man as well as the biosphere as we know it is intimately related to these matters.

The peaceful use of nuclear energy for excavation, gas stimulation, generation of electric power, etc., although not having the dramatic effects of nuclear war, have the potential for insidious long-term effects unless the ecological consequences of these uses are given serious consideration. These considerations are not unique to nuclear energy but are an integral part of any modification of the environemnt by man. Unique to nuclear energy is the disposal of low and high level nuclear wastes.

The reader should refrain from concluding that inclusion in Part V of the vastly different topics nuclear war, waste disposal and peaceful use of nuclear energy implies an equal ecological concern for the three. The grouping exists strictly as a matter of convenience.

RADIOACTIVE FALLOUT PHENOMENA AND MECHANISMS

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(*Presented by* A. W. KLEMENT, JR.)

Abstract—In this review nuclear detonations are briefly described. The characteristics of fallout material and its behavior in the atmosphere are discussed with particular regard to recent findings and theories. An indication of the current fallout situation is given. Reference is made to other reviews as well as to specific research papers and documentations of fallout data.

INTRODUCTION

ONE OF the important sources of environmental radioactivity is radioactive material injected into the atmosphere during nuclear weapons or peaceful explosives tests, reactor operations and space applications of nuclear energy. So far, fallout from nuclear weapons tests has been foremost among these man-made sources from the standpoint of widespread environmental radioactivity. While fallout from any source is characteristic of the source itself, the resulting phenomena observed from fallout from nuclear tests are similar to those found from other atmospheric sources. A brief description of a nuclear detonation,(1) usually referred to as a "shot" or an "event," may be of assistance in defining the topic to be discussed here.

When a nuclear weapon detonates, a large quantity of energy is liberated within a small volume of material. This produces high temperatures in the bomb materials and surrounding air. The temperature in the center of the fireball is several tens of million degrees, approaching that of the center of the sun. All the material is vaporized, producing a spherical luminous mass which is referred to as the fireball. At the time of explosion large pressures are also produced which cause the fireball to expand. During this expansion the fireball decreases in pressure, temperature and brightness. The maximum rate of expansion occurs after about 1 sec. For a 20-kton (equivalent to 20,000 tons of TNT) weapon detonated in the air the maximum diameter of the fireball is about $\frac{1}{3}$ mile and for a 1-Mton weapon about $1\frac{1}{2}$ miles. During the expansion period the fireball is rising at a rate of about 300 ft/sec. After about 1 min, the fireball is no longer visible and has risen about $4\frac{1}{2}$ miles for a 1-Mton weapon.

The rising nuclear fireball and cloud contain radioactive fission products and bomb materials. These materials are vaporized by the intense heat. On cooling, the material is suspended as small particles of different sizes. The particles are carried by the wind in different directions and velocities depending on the size of particle and wind structure at various altitudes. Fallout from a surface burst will begin around ground zero after several min up to about 30 min or more and arrive at greater distances (up to several hundred miles) within 24 h. This fallout is called "early," "close-in" or "local" fallout. The time of fallout depends on yield, height, or depth of burst, weather, and distance from ground zero.

The fission products consist of over 200 different nuclides of about 36 elements between atomic numbers 28 and 65, most of which are radioactive. Most of these decay to stable nuclides by emission of beta particles, usually accompanied by gamma rays. These fission products are produced only in the fission process and their radiation accounts for about 10 per cent of the total fission energy. The amount of fission products formed depends on the *fission* yield of the weapon.

The interaction of neutrons with soil, air, water or parts of the nuclear device at the time of detonation produces some radioactive nuclides, usually referred to as neutron-induced radionuclides. These are produced in both fission and thermonuclear detonations; the

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Klement, A. W., Jr. 1965. Radioactive fallout phenomena and mechanisms. Health Physics 11(12):1265-1274.

amount produced depends on the *total* weapon yield. These induced nuclides may account for a great deal of the radioactivity within the first few hours after a detonation, especially near the site of detonation. Only a few of these nuclides are present in appreciable quantities after a day or so.

Collectively, the decay of radioactivity of nuclear debris may be described roughly by $t^{-1.2}$, where t is time in hours after a specified reference time. One hour after detonation, $H + 1$, is usually used as a reference time for computation of radioactivity at any time. The negative exponent varies slightly with the specific detonation characteristics.

With this brief description of the source of fallout from nuclear detonations an attempt will be made to review some of the specific mechanisms involved in fallout. Particular attention will be given to recent findings, many of which were discussed at a conference in November 1964.(2) Also of interest are current environmental levels of fallout nuclides. Since the transport of nuclear debris and its subsequent entry into biological systems depends on the characteristics of the debris, attention will be given to some of these specific characteristics.

CHARACTERISTICS OF FALLOUT

The physical and chemical characteristics of nuclear debris depend greatly on the type of nuclear detonation producing the debris. The amounts and composition of radioactivity produced are determined to a large extent by the fission and thermonuclear yield of the device and the extent of involvement of surrounding material. The fissionable material used also affects the amounts of fission products. The numbers of variations of source characteristics are much too large to consider in detail here but some general indications of radionuclide production are useful. In Table 1 are shown estimated amounts of several radionuclides which may be expected from idealized terrestrial surface detonations of 1 Mton fission.(3) The amounts of fission products would be reduced in proportion to the extent of the thermonuclear yield and the induced nuclides may differ widely from those shown for different surfaces and height of burst. Among the nuclides listed are those which have been studied in the greatest detail. All nuclides present after deposition except the nuclides emitting β particles only, e.g. ^{90}Sr, contribute to environmental external γ-radiation.

Table 1. *Approximate* amounts of some radionuclides produced by* 1 *Mton* (*fission*) *idealized terrestrial surface detonation*(3)

Nuclide	Half-life	MCi at 1 month	MCi at 1 y
Fission products			
^{89}Sr	53 days	11	0.13
^{90}Sr	28 y	0.10	0.10
^{95}Zr	65 days	15	0.43
^{131}I	8 days	6.3	0
^{137}Cs	30 y	0.16	0.16
^{144}Ce	290 days	3.5	1.6
Induced nuclides			
^{45}Ca	152 days	0.26	0.06
^{55}Fe	2.9 y	0.10	0.09
^{14}C	5760 y	0.03	0.03

* Various estimates based on different fissionable material and neutron energies may differ from these somewhat. Device materials are not included in these estimates.

A number of studies of the characteristics of nuclear debris were conducted during the United States test series in 1962; DOMINIC I at the Nevada Test Site (NTS), DOMINIC II in the Pacific, and the peaceful nuclear cratering shots Danny Boy and Sedan at NTS. One series of studies(4) during three NTS shots of low yield (Johnny Boy, Small Boy and Sedan) showed that gross close-in fallout samples had a "typical" value, or a narrow range of values, for the fractionation ratio of ^{89}Sr/^{95}Zr. "Fractionation" refers to the nonrepresentativeness of the radionuclide composition of a sample compared to a reference composition of all nuclear debris produced in a detonation. Composition is expressed as nuclide ratios. A measure of fractionation is the fractionation ratio, e.g. (^{89}Sr/^{95}Zr in sample)/(^{89}Sr/^{95}Zr produced in a shot). An unfractionated sample would have a fractionation ratio of unity.

For the Johnny Boy surface shot the ^{89}Sr/^{95}Zr ratio was about 0.03, indicating very severe fractionation, while for the Small Boy surface shot the ratio ranged from 0.1 to 0.2, indicating moderate fractionation. This ratio for the Sedan shot ranged from about 0.5 to 3.8, characteristic of such cratering shots as well as venting underground and underwater shots. Fractionation from ^{95}Zr in all these three shots was found for the same group of nuclides.* Three nuclides, ^{99}Mo, ^{144}Ce and ^{239}Pu, did not fractionate in these shots.

Studies during earlier test series indicated that some fractionation* occured during a high-yield coral surface burst and during some air bursts. The nonfractionation of ^{239}Np in the coral surface burst and fractionation of ^{99}Mo in air bursts are exceptions. In Danny Boy, the 0.43-kton cratering shot, Miskel and Bonner(5) reported that relatively small amounts of radioactivity escaped to the atmosphere and the debris was considerably fractionated. These authors concluded that only about 0.2 per cent of the total nonvolatile nuclides, e.g. ^{147}Nd, escaped and was rapidly deposited in close-in fallout. Only about 0.9 per cent of the volatile ^{137}Cs was found in nearby fallout and 12.8 per cent of this nuclide was in the cloud at 8 min after detonation.

In general, studies(6,7) of debris in areas at about 600 miles and 1000 miles from the Small Boy and Sedan shots showed fractionation. No obvious trends were seen among results from the several collection sites. However, except for cerium isotopes, greater fractionation relative to ^{99}Mo was found for nuclides in air filter samples than in fallout collector samples. This difference indicates a greater association of volatile nuclides with the smaller particles collected on air filters than with the large particles in the fallout collector samples. The opposite is true of the refractory (nonvolatile) cerium isotopes. Additional detailed fallout data for the Small Boy shot have been reported by Miller and Sartor.(8)

From studies(9,10) of individual particles or particle size fractions from early cloud samples during DOMINIC II, severe fractionation of single particles with respect to the gross sample was found. Results of these studies point toward condensation of refractory nuclides followed by precipitation of volatile nuclides on the particles at later times. The beta activity of individual particles ($>2\ \mu$) was found to be directly proportional to particle volume and a function of weapon yield. The negative time exponents for decay for individual particles were found to vary from 0.7 to 1.4 with an average of 1.1, and they were independent of particle size. The average is not greatly different from the widely used value of 1.2 mentioned previously.

Particle sizes of nuclear debris vary widely depending on detonation characteristics. For high yield air bursts such as those mentioned in the preceding paragraph, sizes range from submicron to a few hundred microns, while shots associated with large amounts of silicate are generally larger and may be as large as several thousand microns. These large particles fall relatively rapidly whereas the submicron particles, especially those injected into the stratosphere and which appear in global fallout, may remain in the stratosphere for several years. Analyses of four samples obtained prior to resumption of testing in the fall of 1961 at about 110,000 ft(11) showed a median particle diameter of 0.002 μ. The same investigator found a median diameter of 0.008 μ in a sample in October 1962 at 108,000 ft and 0.13 and 0.008 μ in two samples at 106,000 ft in May and June 1963, respectively. Other stratospheric studies(12) during 1962 and 1963 over an altitude range of 30,000 to 100,000 ft show that most of the radioactivity is contained in particles with diameters of about 0.04 to 0.30 μ. During this period the highest concentrations of radioactivity were found at altitudes between about 50,000 and 70,000 ft.

As particles are transported through the atmosphere, association between nuclear debris and nonnuclear material normally found in the atmosphere takes place. Such associations may involve chemical reactions between constituents or other phenomena. These "combining" effects may result in considerable change in particle size and chemical properties of the aerosol containing the nuclear debris in surface air. Also some nuclide compounds may be dissolved in precipitation and subsequently released; this process may alter the radioactivity content of the particles. Lockhart *et*

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* ^{89}Sr, ^{90}Sr, ^{91}Y, ^{103}Ru, ^{106}Ru, ^{131}I, ^{132}Te, ^{136}Cs, ^{137}Cs, ^{140}Ba, ^{141}Ce and ^{239}Np, relative to ^{95}Zr.

al.[13] have concluded that stratospheric debris becomes associated with relatively large nonnuclear particles in the troposphere and produces particles between 0.3 and 1.0 μ diam. in surface air. Particle size distribution also is somewhat restricted. These investigators found some differences in radioactivity content between the largest and smallest size particle fractions although there was no obvious fractionation with particle size. SHLEIEN *et al.*[14] concluded that surface air particles of $< 1.75\ \mu$ diam. contained at least 88 per cent of the total gamma radioactivity. Their samples were collected in the spring of 1964.

ATMOSPHERIC TRANSPORT OF FALLOUT MATERIAL

The behavior of fallout particles in the atmosphere is of interest because it affects deposition rates and patterns. Knowledge of this behaviour is necessary for fallout predictions and assessment of fallout situations. Nuclear debris injected into the troposphere remains in this region a few days to a few weeks. Material in the stratosphere may remain there from several months to several years, with some exceptions which will be mentioned later. Transport mechanisms have been reviewed in detail elsewhere[15–19] and only a brief summary of these will be given here.

MACHTA[15] in a review of the status of global fallout predictions has summarized the processes so far as they are understood. He argued that the airflow in the troposphere should result in a global fallout pattern with the highest deposition at the latitude of tropospheric injection. Air motions of a global nature are mainly zonal, on which are superimposed waves producing longitudinal motions. The effect produced is a band of deposition several tens of degrees wide at the peak and the peak may be somewhat displaced from the source latitude at some locations. MACHTA points out that this pattern is not always found. As one example he claims that debris injected into the upper polar troposphere mixes downward and equatorward along isentopic surfaces. This results in appearance of the debris in temperate latitudes within a period of several days to weeks, and it is therefore relatively available for scavenging by precipitation and downward mixing. A second example is the case of mid- and upper-tropospheric injections in equatorial regions. Here debris is carried poleward and sinks in subtropical regions. In addition, horizontal mixing and wind shear combined with vertical diffusion produce dispersion of debris in the atmosphere. At low altitudes, terrain, particularly mountains and land–water contrasts, affects the movement of debris.

The mechanisms of transport and diffusion of nuclear debris in the stratosphere are much less known than those in the troposphere. Reference is made again to the review of MACHTA.[15] Predictions of movement in the stratosphere are based mainly on empirical models derived from observations of fallout. Current models are based on the use of several stratospheric compartments and an assumed removal rate for each compartment. Establishment of the several models of this kind utilizes to varying degrees current meteorological theories as well as observed fallout data. Several theoretical models are being explored as well. Knowledge of stratospheric motions is gained by basic meteorological observations and by the use of natural and fallout radionuclides as tracers. While much concerning stratospheric processes is not known, a great deal *is* known about some aspects of stratospheric motions and stratosphere–troposphere exchange mechanisms.

NEWELL and MILLER[17] have concluded from their studies of energy and momentum that stratospheric circulation involves the interdependence of adjacent layers of the atmosphere. They state that the driving force for the lower stratosphere must come from the troposphere. The lower stratosphere, in turn, is coupled with the upper stratosphere. An earlier concept, based on energy considerations and tracer measurements of sloping motions in the stratosphere, was developed by NEWELL.[18] There is consistency between these phenomena and the more recent concepts developed by DANIELSEN[19,20] to explain stratospheric–tropospheric exchange of nuclear debris. These involve a folding of the tropopause which extrudes stratospheric air into the troposphere (Fig. 1) and a relationship between concentrations of radioactivity and layers of the extruded air. This folding process is frequently seen.

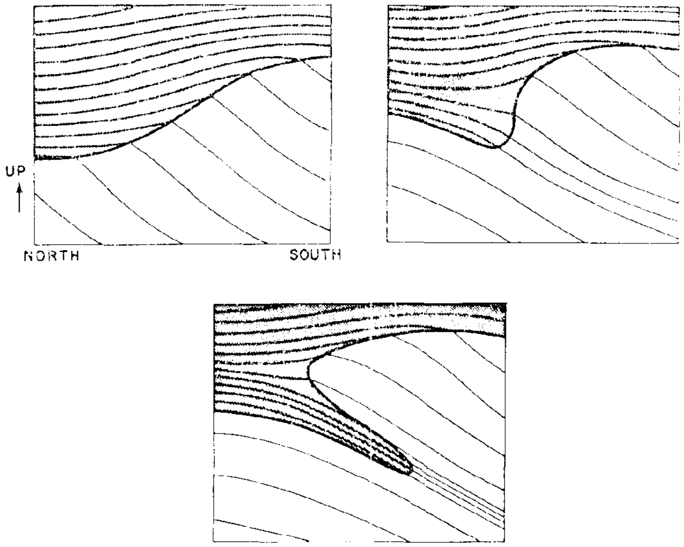

FIG. 1. Cross sections of the atmosphere looking toward the east showing the development of an extrusion of stratospheric air (shaded area) into the troposphere (white area) through a steepening and folding of the tropopause (heavy lines). The concentration of lines of equal potential temperature (light lines) are lines along which air can move most freely (courtesy of E. F. DANIELSEN, Pennsylvania State University).

The radioactivity thus transported downward acts as a source of stratospheric debris at low altitude. Experimental observations(19–22) support these concepts and suggest a method for predicting areas of relatively high radioactivity ("hot spots") and short-lived nuclides during periods shortly after the injection of fresh nuclear debris into the stratosphere.

ENVIRONMENTAL CONSIDERATION OF FALLOUT

While the mechanisms of transport of radionuclides in the biosphere are not understood in detail, much is known about the species and amounts of many nuclides that are transported among specific parts of systems. Knowledge here is gained through direct measurements of concentrations of radionuclides in the various environmental materials. A primary purpose of this symposium is to review this area of research. Other sessions also are devoted to this subject. Reference to previous literature(23,24) may be useful. It is of interest to present here an indication of environmental levels of fallout radioactivity, and to review the extent of nuclear testing producing these levels.

Summaries of yields of weapon tests(25) and information on announced shots(26) are available. In Table 2, fission and total yields of nuclear tests through 1962 are summarized so far as they are important to large-scale fallout deposition. Tests which injected debris above 150,000 ft, releases from underground shots, and low yield surface shots are not included in Table 2

Table 2. Approximate fission and total yields of nuclear weapons tests conducted in the atmosphere by all Nations(25). (Yields in Mtons)

Inclusive years	Fission yield Air	Fission yield Surface	Total yield Air	Total yield Surface
1945–1951	0.19	0.52	0.19	0.57
1952–1954	1	37	1	59
1955–1956	5.6	7.5	11	17
1957–1958	31	9	57	28
1961	25		120	
1962	76		217	
Total	139	54	406	105

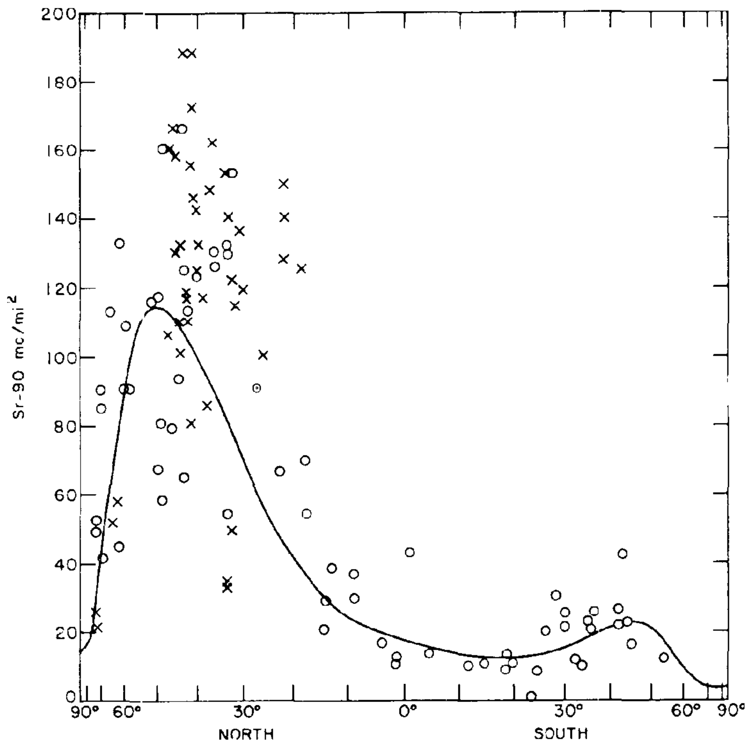

FIG. 2. Distribution of ^{90}Sr deposition by latitude in late 1963 (courtesy of R. J. LIST, U.S. Weather Bureau).

since they contribute little to current fallout levels. In 1961 the USSR tests injected debris equivalent to 25 Mtons fission into the stratosphere. During the U.S. and USSR tests in 1962, 71 Mton fission was injected into the stratosphere. In terms of a specific nuclide of interest, 10 Mtons of fission produce about 1 MCi of ^{90}Sr. Correcting for decay to late 1963 (about 2-1/2 per cent per year), the estimated total production of ^{90}Sr is 19 MCi. At that time about 7.6 to 8.6 MCi ^{90}Sr, according to LIST *et al.*,[27] had been deposited worldwide with a mean latitudinal distribution as shown in Fig. 2. The highest deposition, averaging about 115 mCi ^{90}Sr/miles^2, is seen at about 50°N. A minimum of about 10 mCi/miles^2 is seen in the equatorial region and another peak of about 20 mCi/miles^2 appears at about 40 to 50°S. Deposition south of 70°S is estimated to be quite low. The range of values seen at a specified latitude reflects variation in rainfall and perhaps other meteorological phenomena. Levels of ^{90}Sr in the U.S. reported by these authors[27] are shown in Fig. 3. Within latitude bands, fallout deposition is proportional to precipitation, plus a small increment due to dry fallout.[28] Exceptions are seen in northern Utah and in the northern Central Plains. Neither of these appear to be caused from local fallout from tests at the Neveda Test Site, although these tests have contributed to fallout levels in these areas, and are not well understood.[27] Deposition of ^{90}Sr through 1963 and expected subsequent deposition in the U.S.[29] are summarized in Table 3. Deposition during 1966 will probably be about half that during 1965. Some data are available for other nuclides.[30] Based on these data and ^{90}Sr levels, estimates may be made of deposition levels of several nuclides. External γ-radiation

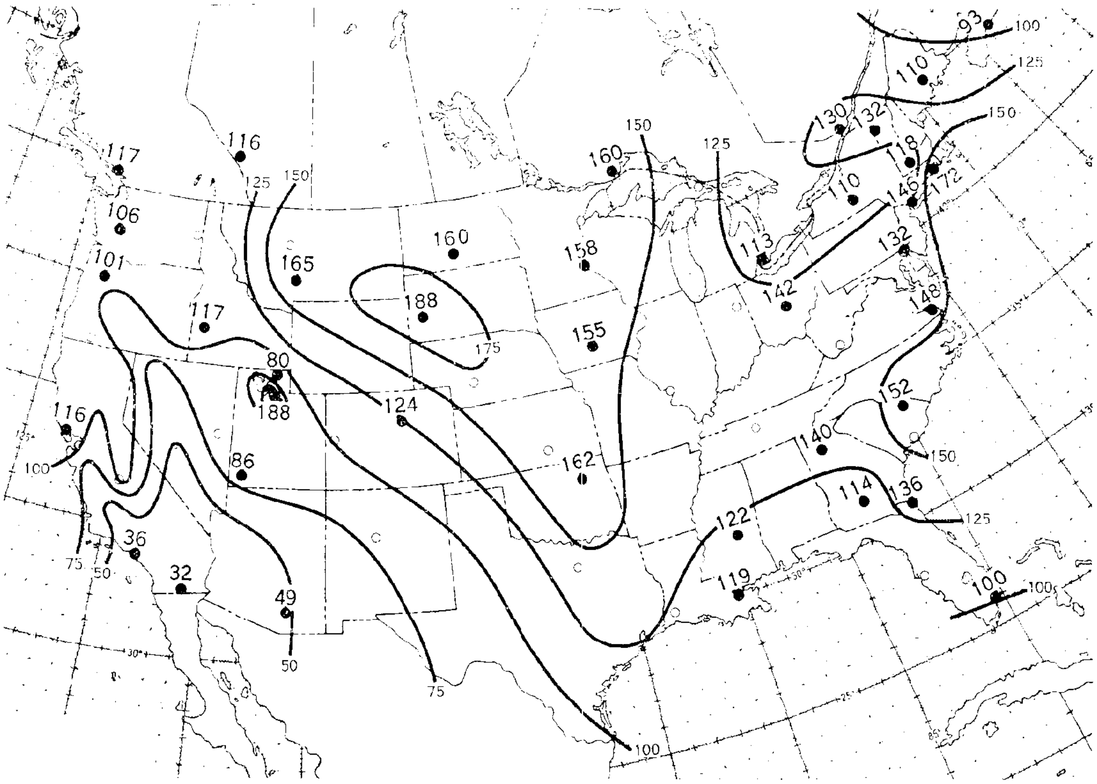

Fig. 3. Estimated distribution of ^{90}Sr in the U.S. in late 1963 (courtesy of R. J. List, U.S. Weather Bureau).

Table 3. Estimated deposition of Sr^{90} *in the U.S.*$^{(29)}$

Years	Rainfall region of U.S.*	Sr^{90} deposition (mCi/miles^2)
Accumulated through 1963	"Wet"	150
	"Dry"	65
Increment 1964	"Wet"	30
	"Dry"	12
Increment 1965	"Wet"	15
	"Dry"	6
Increment after 1965	"Wet"	25
	"Dry"	10

* Regions are roughly separated by the 20 in. rainfall isoline.

levels due to fallout generally follow distribution patterns similar to those for ^{90}Sr. Levels by region in the U.S. from a survey during 1962 to 1964$^{(31)}$ are summarized in Table 4. It is seen that levels in the U.S. range from about 0.5 to 7 μR/h. Corresponding levels of natural γ-radiation range from about 3 to 19 μR/h.

Table 4. Summary of regional γ-radiation levels in the U.S., survey—1962 *to* 1964

Region of U.S.	γ-Radiation ranges (μR/h)$^{(31)}$ Natural	Fallout
Northeast	4–15	0.5–5
Southeast	3–19	2–7
Central	7–9	2–6
West	3–15	1 5

The levels of radionuclides reported in the paragraph above are *deposition* levels and are indicative of the extent of fallout. No meaningful summary of deposition data for the U.S. is possible from the standpoint of accumulation of fallout nuclides in localized biological systems. Of particular importance in ecological studies are fallout *rate* and the time sequence of deposition since direct deposition on plants is a major factor in the accumulation of fallout radionuclides.(16,32–34) Also, in regard to uptake from soil one must consider cumulative levels of nuclides in soils and their distribution in depth as they are affected by weathering and other disturbing influences, in addition to other ecological factors. In most soils in the U.S., ^{90}Sr does not appear to leach very rapidly and nearly all of the ^{137}Cs is found near the surface of undisturbed soils. In medium-to-fine textured soils about 75–80 per cent of deposited ^{90}Sr is found in the upper 2 in. and even in medium textured soils similar proportions are found in the upper 4 in.(35,36) Virtually all of the ^{90}Sr is contained in the upper 8 in. of nearly all U.S. soils. Plants obtaining nutrients from near the surface of soils would therefore take up greater amounts of ^{90}Sr and ^{137}Cs than would other plants. Cultivation and other disturbances would affect the concentrations of these nuclides available to plants, however.

For predicting average ^{90}Sr and ^{137}Cs levels in foods and total diet for relatively large areas and for periods of a year, a simple relationship is used. This relationship takes the following form,(16,32,33) and presumably it would be applicable to many terrestrial organisms under the conditions stated.

$$C = aA + bB$$

C is nuclide concentration, A is cumulative deposition per unit area, B is deposition rate per unit area, and a and b are empirical "proportionality constants." The values of a and b vary widely with the material of interest and meteorological and agricultural conditions. They are known only for some agricultural plants. The value of a approaches zero for some plants such as Spanish moss (*Tillandsia usneoides*) and some lichens, while b is near zero for plants sheltered from appreciable deposition on foliage. Obviously, when and where the proper conditions exist and the various factors are known, reasonably good predictions can be made. However, caution is required in applying such relationships for specific organisms or systems, particularly over short time periods. Also, it is well to remember that the actual mechanisms are complex.(34,37–40) Application of such a simple empirical formula does not imply an understanding of the mechanisms of transfer into and within a system. An important area of ecological research has this understanding as an objective, one not unique to radionuclides.

It has been difficult to obtain explainable relationships between concentrations of fallout nuclides in surface air and in other environmental media, including precipitation, soil, and biological systems. Some qualitative information on precipitation(37,41,42) has been found but further study is necessary before relationships will be clearly defined. Data are available on concentrations of fallout radioactivity in air.(43–46) Peak concentrations, similar to those in deposition rates, are seen during the spring of each year and are related to the entrance of debris from the stratosphere during late winter, spring or early summer. After new tropospheric injections of nuclear debris, peaks in air concentrations are seen also along the path of a nuclear cloud. As one may expect, such data are useful for determining arrival times of debris at specific locations, and estimating inhaled radioactivity. Levels of gross β fallout radioactivity in U.S. surface air(46) in January 1965 were of the order of 0.1 to 2 pCi/m^3. Levels in March 1965 ranged from 0.1 to 3 pCi/m^3.

While short-term variations in fallout deposition are probably not as detectable in fresh surface waters as they are in surface air, seasonal variations are seen. These variations generally follow the spring peak effect, as found for deposition rate and amounts in surface air. Relative concentrations of fallout ^{90}Sr in surface waters(47) generally vary in accordance with local deposition rates and the characteristics of the aquatic environment. Since runoff and flow play an important role in fresh surface water nuclide concentrations, large differences are expected from one location to another within a major river or lake. During the period

July 1963 to June 1964, quarterly average concentrations of ^{90}Sr in the Red River at Grand Forks, North Dakota, were the highest reported by the Public Health Service.(47) Levels at that location were 11.3, 7.1, 4.9 and 9.4 pCi/liter for the four quarters respectively, and indicate the general trend. The arithmetic mean concentration of ^{90}Sr at 69 sampling locations in the U.S. during April–June 1964 was 3.0 pCi/liter. The median value was 2.3. These were about 0.5 pCi/liter higher than the previous quarter. Levels at other locations were as much as 10- to 30-fold lower.

SUMMARY

In this review nuclear detonations have been briefly described. The characteristics of fallout material and its behavior in the atmosphere have been discussed with particular regard to recent findings and theories. An indication of the current fallout situation of general interest to ecologists is given. It is emphasized that researchers in nuclide cycling must determine the fallout situation within the specific systems to be studied in addition to other environmental factors. As in any review, particularly one such as this which attempts coverage of a relatively broad scope, reference to the literature is of value to those desiring detailed information. For this reason reference has been made to other reviews as well as to specific research papers and documentations of fallout data.

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FORECASTING LONG-RANGE ECOLOGICAL RECOVERY FROM NUCLEAR ATTACK

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INTRODUCTION

Ecological effects of nuclear attack have been considered in numerous lectures, committees, conferences, panels, seminars, study groups, and workshops. A deluge of books, manuals, pamphlets, reports, and newspaper articles, often referencing a minimum of scientific manuscripts, have resulted. As nuclear testing has been conducted in few and rather specialized ecosystems, and under rather specific sets of circumstances, little unequivocal data exist to forecast ecological damage and recovery. Consequently, ecological predictions of postattack effects, being extrapolated from these few nuclear testing sites, from laboratory experimentation, from irradiation of several specific ecosystems, and from analogies of catastrophic events in nature, result in controversy.

Indications of the amount of thinking and the range of viewpoints concerning ecological effects and recovery from nuclear attack can be quickly gleaned from publications produced by the Technical Analysis Branch (Division of Biology and Medicine), U. S. Atomic Energy Commission, Washington, D. C. 20545 (particularly compilations of R. Lord and L. Eberhardt); the Hudson Institute, Inc., Quaker Ridge Road, Harmon-on-Hudson, New York 10520; the Stanford Research Institute, Menlo Park, California; the National Academy of Sciences - National Research Council; books such as Stonier's Nuclear Disaster[1] and Anderson's Thermonuclear Warfare[2]; the Proceedings of the Symposium on Ecological Effects of Nuclear War[3]; and several congressional hearings[4,5,6]. Succinctly summarized, according to the current status of knowledge, huge fires would likely -- would likely not -- result[5,6,7]; fire produces highly unfavorable -- favorable -- effects[8,9,10,11]; climatic and weather patterns would -- would not -- be altered[1,12,13,14]; outbreaks of insects, rodents, disease are likely -- are not likely -- to occur[1,15,16,17,18]. Regardless of choice, one seemingly can find published support for an extremely pessimistic "nothing can survive" view to an optimistic one "predicting ecological damage would go almost unnoticed."

Nevertheless, despite controversy, emotion, continuous repeating of unsupported statements and lack of incontrovertible facts, some points of general agreement are emerging. Hopefully, we can begin to

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Osburn, W. S., Jr. 1968. Forecasting long-range recovery from nuclear attack. pp. 107-135. In: Proceedings of the Symposium on Postattack Recovery from Nuclear War. (Anonymous). National Academy of Sciences, National Academy of Engineering, National Research Council, Washington, D. C.

use somewhat smaller brush strokes in painting the picture of long-term ecological effects of nuclear war than those suggested by John Wolfe in the 1959 Congressional hearings, ".....only a general picture can be painted, and that in broad strokes."[6]

This manuscript proposes to discuss the following: What are indications from the data most nearly relevant to nuclear war consequences, i.e., ecological studies of nuclear-testing sites, of gamma-irradiated ecosystems and of a radioactive-lake bed? What is the consensus of opinions regarding factors or conditions associated with ecological recovery from nuclear war -- fire, floods, erosion, weather modification -- and would ecological recovery materially impede national recovery? What radioecological theories or principles have been or are being developed which may be helpful in predicting radionuclide fate, radiation effects, and ecosystem recovery? Areas of weakness in ability to predict, and how we can perhaps improve accuracy of predicting ecological consequences from nuclear warfare, are considered throughout the manuscript. In addition, and perhaps of greatest value, will be the literature referenced. Care has been taken to see that, in addition to citing authors who have put forth estimates of ecological recovery from nuclear attack,there are also incorporated basic research data concerning factors most often considered to be of greatest importance in contemplating ecological damage and recovery.

SUPPOSITIONS GAINED FROM STUDIES MOST NEARLY RELEVANT TO NUCLEAR WAR CONSEQUENCES

What have we learned from: (1) studying ecosystems directly damaged by testing of nuclear devices, e.g., the Pacific Atolls, the Nevada and New Mexico desert ecosystems, (2) studying ecosystems subjected to relatively large exposures of chronic and/or acute ionizing radiation (gamma sources) from controlled sources, in one case those ecosystems typical of northeastern and southeastern United States, and in the other a tropical rain-forest ecosystem, and (3) studying a radioactive lake bed formed by draining a lake used for nuclear-waste disposal?

In the case of Pacific Atolls, quotations taken from the summarizing chapter of Hine's 1963 publication, Proving Ground, An Account of the Radiobiological Studies in the Pacific 1946-1961, demonstrate a rather optimistic outlook. "...Populations of animals and plants observed under field conditions--the sea urchins of Bikini in 1947, the grasses and shrubs restoring the natural cover of Eniwetok shot islands, or the rats of Engebi--exhibit a capacity to maintain themselves even in environments that have been exposed to the full effects of nuclear blast and to levels of radioactivity that all laboratory experiences indicate were totally lethal;..." and the field crews "...developed a confidence during the years of the healing powers of the natural environment..."* "They had seen islands swept clean, water churned, and the damage created by heat, pressure, and radioactivity..., and nowhere that they had studied the long-term effects of radioactivity as a separate phenomenon was there evidence that normal regrowth was not occurring."[19]

Dunn, Spellman, and Hess, after following periodically (1947-1950 and 1963-1965) the revegetational history of the first atomic bomb test site in New Mexico, U. S. A., reported the following: "The extent of the disturbance of the 'climax' through denudation was such that essentially the full sequence of successional stages described by Clements has followed," and further, "within a few days after detonation seeds were washed into the center of the crater and plants have been growing there since."[20] While vegetation apparently has not recovered its original status in the 20 years since testing -- recovery from disturbance is known to be slow in desert regions -- succession appears to be normal.

Moreover, results from irradiated plant communities on Long Island in New York State,[15] in Georgia,[21] within a Puerto Rico tropical montane rain forest (H. T. Odum, personal communication), and communities of the Southeastern U. S. (McCormick, unpublished data) indicate recovery apparently follows natural successional sequences.

At Oak Ridge National Laboratory, an artificial lake -- White Oak Lake -- was used for disposal of tons of radioactive wastes. Upon draining, soil surface radioactivity was too high to be considered safe to work upon for a considerable amount of time, but plants and animals invaded and quickly became quite well established.[22]

The one very important result common to all the above studies is that ecological recovery follows normal predictable successional trends, i.e., successional patterns following damage from radiation are the same as those following fire, logging, or other natural catastrophic events. As there is no reason to expect that ecological-recovery sequences worked out for other major U. S. vegetation types would not follow a similar path, we find strong support for two suppositions. The first is support for John Wolfe's 1959 summation in which he anticipates that biotic succession would lead to full ecological recovery of landscape patterns "...probably not unlike the primeval distributions of forest, woodland, desert and grassland on this continent."[5] The second supposition is that progress towards predicting ecological recovery from nuclear war is closely related -- possibly limited -- to our general ecological knowledge. On the one hand this situation can be heartening in that we can benefit from the past 50 or 60 years of ecological study, yet on the other hand, it can be dismaying in that we have developed so few guiding ecological principles.

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* The concept of ecosystem healing power or resiliency is one frequently propounded by researchers of irradiated systems.

CONSENSUS OF OPINIONS REGARDING FACTORS RELEVANT TO ECOLOGICAL RECOVERY

A number of speculative postattack ecological-recovery situations have been constructed -- some quite grim. In forecasting these hypothetical sequelae of a nuclear attack, and in lieu of experimental data, resulting models, riding upon unproven tenets, extrapolations, and arbitrary assumptions produce quite different expressions of consequences. However, a number of factors or conditions are universally discussed, for example, fire, floods, erosion, weather modifications, and whether ecological recovery would materially delay national recovery.

This section of the manuscript (1) gives predictions of authors who have reviewed questions of postattack consequences in terms of fires, erosion, weather modification, rate of ecological recovery and ecosystem imbalances, (2) comments upon flaws of prediction and how the reliability of predictions could be increased, and (3) concludes with statements regarding likelihood of ecological damage delaying national recovery.

Role of Fire in Postattack Considerations

Predictions of fire impact on various ecosystems range from "essentially no damage" up to "a holocaust of firestorms from which recovery would be delayed for decades or centuries." As with most things ecological, results hinge heavily upon the sequence of environmental events before, during, and after a nuclear attack. Conditions influencing fire effects have been reviewed by most authors cited in the introduction, and several have attempted to construct postattack prediction models. Given a particular set of environmental conditions, ecological effects of fire are reasonably predictable. As these conditions -- drought, winds, etc. -- which dictate the magnitude of fire effect are presently far beyond our prediction capability, estimation of fire effects from nuclear warfare will be correspondingly limited.

Quotations from several authors provide what seem to be a consensus of opinions concerning important aspects influencing the role of fire in attack and postattack considerations: initiation of fires (flammability of wildland fuels), spread of fire, influence of biota, and secondary fires.

Hurschke has recently prepared a memorandum in which probabilistic estimates have been calculated for the quantities of U. S. wildland fuels that would be simultaneously flammable at a given time of the year.[23] In preparing this report, Hurschke contrived a wildland-fuel distribution, a phenological basis for calculating growth-stage-dependent burning indices, and a method for simulating the fire-depressing effect of snow cover. Results graphically depict the annual cycles of simultaneously flammable area for eight different fuel-type combinations -- e.g., grass, brush, softwood trees, hardwood trees, etc. These eight fuel type areas actually represent conversions from the 116 plant community units mapped by Kuchler in Potential Natural Vegetation of the Conterminous United States, 1961."[24] Reading these graphs is quite easy but interpreting them requires caution. In fact, as the author points out, no direct quantitative extrapolation from these results to damage assessment is possible without considering a number of other variables such as time of day, distribution of ignition points, and physical limitations to fire spread. Though the compilation contains few surprises, the use of probability language seemingly provides us with something more meaningful than such terms as "often" or "frequently."

In congressional testimony, J. E. Hill made cogent arguments in considering catastrophic fires.[6] He argued that very special conditions are necessary to initiate great conflagrations: several preceding years of drought, plus several rainless weeks immediately before an attack; in turn the attack must be accompanied by strong, dry winds and a large fuel source. These conditions occur relatively infrequently and seldom, if ever, over the entire United States at any one time. Consequently, the incidence of catastrophic fires in the United States is approximately 11 years apart. Once started, these fires are seldom stopped by fire-fighting but by natural, topographic barriers or by a shift in weather conditions. He (Hill) concludes that "large free-running catastrophic forest fire would occur very infrequently as the result of the detonation of a nuclear weapon."

A. Broido, in discussing the effects of fire on major ecosystems, concludes "...the ecological consequences of the fires that may occur after a nuclear catastrophe are not expected to differ seriously from the consequences of holocausts of the past" and "though we have experienced large fires since prehistoric times, interpretation of their effects on major ecosystems, are still quite controversial -- whether one considers the effect on plant succession, on animal life, on plant diseases and pests, on the chemical composition of the soil, or on such physical factors as temperature and humidity."[8]

The above quotations present brief but reasonable summations concerning fire in nuclear-attack situations. However, I would like to suggest two other likely important considerations which have received scant attention, but could be researched readily: (1) Redistribution of fallout nuclides by fire, and (2) Subdividing the geographical region to be studied according to some standard division.

Data concerning the effect of fire on the redistribution pattern of nuclear fallout are essentially nonexistent; a small study involving a cheat-grass ecosystem near Hanford, Washington, appears to be the only exception.[25] Yet, a fire occurring during or subsequent to fallout deposition would almost certainly place fallout nuclides on the ground surface in a highly erodible situation. Thus wind and water redistribution could cause high concentration in sites frequented by man, such as fence rows or along water courses. Odum points out it might be desirable to burn badly contaminated vegetation as a recovery measure.[26] This is based upon the assumption that there would be reduced fallout entering food chains, since newly produced plants, growing either from regeneration of shoots that sprout from buried and little-contaminated rhizomes or seeds, would have much less foliar contamination. Regardless of whether fire could be used as a decontamination process, the matter of fire and fallout redistribution should be further researched. The radiation level of some long-lived fallout nuclides is still high enough within some natural ecosystems to locate sites of concentration. Extensive fires have occurred and will likely continue to occur within these several U. S. vegetation types. Consequently, well-designed research projects might enable a rather clear picture of fallout redistribution by fire and subsequent erosion to be obtained. In addition, studies of present day patterns of wind-drifted snow or soil, especially in prairie regions, could well be used to anticipate nuclide redistribution after a nuclear attack.

Many discuss fire effects, some with rule-of-thumb statements such as "critical fire-spread conditions correspond roughly to maximum visibility," while others insert complex physical heat laws and formulae.[27, 28, 29, 30] Often, crudely derived assumptions regarding factors which play major roles in forecasting fire effects are combined with quantitatively derived data on factors which may play an insignificant role but happen to be easy to measure precisely. Sometimes a discussion follows refining predictions to fractions of a percent. This sort of treatment tends to lead the user into a false sense of security with respect to the validity of his results.

Inherent with predictability in general, problems enter because regions into which inquiry is being made by various nuclear-damage-and-recovery prognosticators are not homogeneous in terms of weather patterns, fuel quality and quantity, soil moisture, or other pertinent conditions. It would seem that rather than each individual subdividing the U. S. into a number of little-researched units, poorly known ecologically, he would refer to some standard landscape division, such as Kuchler's division of 116 units.[24] Basic to these units is the idea of homogeneity -- e.g., of vegetation density, height, phenology, etc. -- factors which almost surely influence ignition of fire, extent of fire, heat, area burned, and completeness of the burn. If data were organized according to these units, one could better rely upon past and present ecological research to help answer questions.

Summary considerations in regard to the role of fire are that most forests are remote from expected nuclear targets; approximately half of the lumber in the United States is privately produced and many of these private companies farm -- i.e., use stocking-harvesting regimes, maintenance of firebreaks and lookouts -- according to methods which provide maximum fire protection to their forests; many important lumber-producing conifers exhibit a wide range of preadaptations to fire, such as having serotinous cones which require heat to open them, or needing mineral soil for good seed germination and survival, or being able to sprout when aboveground portions are killed, or having growing tip thickly protected by dense needle clusters, or being able to dissipate heat rapidly, thus protecting the important cambial layer. The U. S. Forest Service is continuing its research into providing better methods to provide natural fire control to their forested regions. Hence, forests would not be expected to be extensively damaged, and the outlook is reasonably optimistic that no lack of forest products would keep national recovery from proceeding without serious interruption.

Role of Water and Wind Erosion in Postattack Recovery

Since severity of erosion would be directly related to the extent of fire damage, and since the consensus of opinion is that fire damage would not materially delay ecological recovery, it follows that erosion problems also would not hamper recovery. However, it is well to consider the role of erosive forces following a nuclear attack, since the above supposition might prove incorrect and since fire damage on a local basis might be severe.

The possibility of increased damage from water and wind erosion is related not only to the extent of damaged and burned vegetation, and upon the weather regime during and following the attack, but also upon a host of characteristics of the burned landscape, i.e., how large and complete the burn, the time of year, topography, amount, location, and vitality of remaining organisms, especially their reproductive potential.

H. H. Mitchell summarizes a preliminary survey of postattack flooding: "The damage that could be caused by postattack floods appears, then, to be small in comparison with the devastation caused by primary effects of a thermonuclear attack: blast and thermal and nuclear radiation."[31] He points out there is a distinctive set of conditions which determines the characteristics of floods such as seasonal distribution of rainfall, snow-melting behavior, and porosity of soil. Consequently, devastating floods rarely occur, and when they do, it is regardless of vegetation-cover conditions. Hence, because of seasonal variation, postattack problems will depend upon the time of year in which a nuclear attack is assumed to occur.

Mitchell further notes that it would be advantageous to analyze data already collected for major drainage regions of the United States so that over-all probabilities of flood damage can be determined for various seasons.

The report paints a rather little-effect picture. True, the ground cover or the water-holding capacity does not significantly alter maximum floods. However, many serious floods can be moderated or prevented by soils with a large water-holding capacity. The number of references cited for this study are meager, and most of the citations are not from journals, but books 30-or-more-years old. When one considers the enormous amount of research that has been done on flood control and relationship of disease and flooding, this study may have litle validity.

Katz, in an excellent compilation concerning nuclear war and soil-erosion problems and prospects, discusses basic factors governing soil erosion and concludes that, despite complexities of the many factors, runoff conditions can be calculated at least approximately. He particularly stressed that better methods of calculating runoff conditions can be derived.[32] As these data are available to make reasonable postattack flood predictions, it is regrettable that it has not been done.

In addition to direct flood damage, water erosion could well be a powerful force in decreasing or increasing radiation hazard via redistribution of radioactive fallout. Though absolute levels can not be predicted, gross patterns of radiation, less intense on steep, unvegetated terrain and with concentration on flood plains proportionally greater, can and should be estimated.

As in the case of water erosion, wind has the potential to alter ecosystems by redistribution of radioactive nuclides or topsoil. Few data exist to make reasonable estimates, though reports by Alexander, et al, and Osburn indicate the magnitude of redistribution of fallout via wind may be relatively large.[33,34,35] In any case, studies could now be designed in which snow-and-top-soil-drifting patterns could be studied in order to indirectly assess potential soil and fallout redistribution.

The possibility of creating a great-plains dust bowl by plants being killed from radioactive fallout has been frequently discussed.

However, I would not expect this, at least in uncultivated regions, as several million years of fire evolution of grassland ecosystems has shaped the development of many plant species that are fire, and likely radiation, protected. First, the radiosensitivity of some of the major grassland component species appears to be rather low (Whicker, personal communication). As Woodwell points out, even though 50 percent of the species might be killed, dry-matter yield might not be diminished.[36] Secondly, even if all plant shoots were killed, many grasses would be regenerated from deep lying rhizomes protected from ground-surface-fallout radiation and from fire, by several inches of soil. Finally, even if plants were killed and ground-surface radioactivity remained too great for young shoots to withstand, it would be several years before roots would decompose enough for their binding power to become insufficient to resist complete wind erosion of the soil.

Modification of Weather

Many have conjectured about how nuclear explosions could affect or influence weather.[13,14,37,38, and others] However, as bomb-produced phenomena are generally an order of magnitude below that of many naturally occurring events such as volcanoes, most scientists have concluded that there would be no measurable effect on the weather more than a few miles distant from a nuclear detonation. However, Batten concludes "...that our knowledge is yet insufficient to provide unambiguous answers."[39]

Rate of Ecological Recovery or Ecesis

The rate of ecological recovery typically receives relatively little attention other than to state it is influenced by a number of environmental and biological circumstances. One consideration which has failed to receive adequate ecological attention is the size of the area of damage. Reestablishment of an ecosystem depends upon a process called ecesis (plant and animal invasion and establishment[40]). A good deal of research has been accomplished in particular landscape regions of the United States and these data could be brought to bear if one were considering recovery for that particular type of landscape. However, when the U. S. is considered as one unit, extrapolated information regarding dynamics of species invasion and establishment is likely to be invalid. Inherent problems concern a number of ecological concepts such as minimal ecological areas, population dispersal, competition, and others.

Ecosystem Imbalance

One major area of agreement among those who have devoted time to considerations of ecological damage and recovery from nuclear attack concerns the creation of an imbalance within an ecosystem whereby outbreaks of insects, rodents, and disease might be anticipated.[41,42,43]

Actually, what happened following dust deposition in the Colorado snowfields in 1963 was as follows: the early-season snow-melt rate was much more rapid than one could expect from air temperature, and streamflow did increase. However, the June peak runoff failed to rise to ordinarily expected levels, let alone exceed them. The reason for this failure follows: the initial deposit of dust, as measured in the Boulder city watershed, was approximately 20 grams per square meter, but rapid melting, removing water and leaving dust and incorporated debris, soon caused the surface of the snow to become coated by an insulating cover, materially reducing the melting rate. Hence, rather than generating a flood, the dust created a situation whereby streamflow was more moderate and extended over a longer period of time than usual.

Another example of how an ecological extrapolation, or perhaps oversimplification in this instance, may be misleading is in the following statement: "For example, we know that insects can destroy food crops, that insect populations are controlled by birds that eat them, that birds are much more radiosensitive to radiation than insects, and, therefore, that radiation from a nuclear explosion may cause a sudden incursion of insect damage to the food supply,"[44] Though birds are known to control insect populations in specific situations, it is a gross oversimplification to suggest that birds are the only, or even a major, control of insect outbreaks. The danger of unproven, poorly supported or partially true tenets, such as birds controlling insects or insect outbreaks occurring in radiation-damaged areas, is that they are so appealingly simple they have been often quoted and could become guiding rules simply by repetition.

Models, such as Ayre's scenario presentations,[45] while excellent means of portraying ecological damage and recovery, result in the presentation of ecologically incompatible, if not impossible, situations; this is caused partly by lack of pertinent ecological data and partly by failure to select pertinent and plausible happenings.

Anticipated Ecological Damage and Recovery

As previously stated, the ecological aftermath of a nuclear attack is highly speculative. However, a consensus of opinion of most ecologists who have seriously considered the problem may be summed up by the following:

"...and that ecological disturbances would not be such as to prevent recovery";[6] "...ecological imbalances that would make normal life impossible are not to be expected";[46] "...direct radiation effects from nuclear war on vegetation are not likely to seriously limit man's reconstruction of his renewable resources."[21]

Literature abounds with examples wherein ecosystem balance was destroyed by introduction of an animal or plant; jackrabbits in Australia and New Zealand and cheat grass in western United States are familiar examples. Outbreaks of locusts, spruce-bud worms, field mice, etc., occasionally occur. At present it is difficult to anticipate if, what, and how regulatory factors might or might not compensate for particular imbalances after nuclear destruction. However, several considerations should be examined. Insects and rodents which have high reproductive potentials and can most readily take advantage of additional sources of food or lack of predation may undergo phenomenal population increases. However, as ecological research progresses, we become better able to read signs of impending population explosions or plague outbreaks long before they occur. And as situations favorable for outbreaks usually take a reasonable amount of time to ripen, one may eventually be able to develop a program of preventative control which would keep pest populations reduced so that their build-up after a nuclear attack would be proportionally delayed. Hence research is needed concerning species which exhibit great population irruptions, have high reproductive potential, and would be directly or indirectly injurious to man or his supply of resources. It would be especially beneficial if some sort of table could be developed which would provide an index of population level, circumstances, and likelihood of an explosive increase.

Flaws or Weakness Commonly Contained in Predictions of Ecological Recovery from Nuclear Catastrophy

Authors of articles dealing with nuclear-war damage or ecological recovery often present convincing arguments. However, when their conjectures concern areas in which one is quite familiar, one frequently finds serious flaws in their predictions.

A common flaw in predicting postattack ecological phenomena concerns extrapolation of an effect or process, valid for a particular region, to a situation far removed ecologically. An example is Stonier's description of a hypothetical postattack sequence of events which would lead to catastrophic flooding.[1] This hypothetical situation was based upon what appeared to be a reasonable translation of an occurrence in northern Europe to a situation in the Rocky Mountains of Colorado. Briefly, and in actuality, in 1963, a layer of dust, presumably from Utah, was deposited on high mountain snowfields in Colorado. Stonier theorized: in northern Europe, farmers cover snow with coal dust to increase heat absorption and thereby proportionally increase the rate of snow-melt. As nuclear-killed landscapes would undoubtedly generate extensive dust available for deposition on snowfields, one could reasonably expect a corresponding increase in spring-snow-melt rate and the level of streamflow increased to the point where huge floods would result.

RADIOECOLOGICAL PRINCIPLES

As expressed above, most individuals considering ecological recovery from nuclear attack believe resulting ecological imbalances would not effectively delay national recovery. However, as many uncertainties exist, expecially concerning long-term consequences, continued research is urged. As research continues, prospects for improving capability for predicting both fate and effect of ionizing radiation steadily improve. Techniques or methods, henceforth referred to as hypotheses or principles, which have helped or offer promise to improve the validity of predicting postattack recovery, will be discussed. In actuality, most of these hypotheses should be considered as interim statements requiring further evaluation and testing before they become firmly established in radioecological considerations.

Principles may immediately be categorized into two groups: those principles which help predict effects of ionizing radiation, and those which help predict fate of fallout nuclides.

Hypotheses which Aid in Predicting Ecological Effects of Ionizing Radiation

Numerous studies show promise of increasing our ability to predict effects of ionizing radiation at various levels on individual organs, whole organisms, or plant and animal assemblages. Within this manuscript, only those studies which show greatest promise of developing an hypothesis most directly applicable to forecasting ecological recovery from ionizing-radiation damage will be discussed. Subjects to be discussed concern predictions of: (1) radiosensitivity of vascular plants, seeds, and mammals; (2) interactions of ionizing radiation and other environmental stresses; and (3) relation between evolutionary development (or life form) of plant communities and radiosensitivity.

(1) Radiosensitivity of plants, seeds and animals.

Perhaps the most promising find, one which may well be considered a principle, is that developed by Sparrow and colleagues wherein a correlation between the volume of cell and nuclei and radiosensitivity of plant meristem cells has been demonstrated.[47] This volume is reasonably constant within a species, and plants with larger chromosome volumes at interphase are proportionally more radiosensitive. Thus, it has been possible to establish plant-radiosensitivity-regression curves, relating interphase chromosome volume to radiation exposure, using various end points such as slight effect, severe growth inhibition, and lethality. These regressions can then be used to estimate the expected radiation tolerance of species for which directly determined data are unavailable. Using the above method and by actually irradiating test plants, Sparrow has compiled a highly useful table of radiosensitivity estimates of a large number of higher plants.

Sparrow and Woodwell tested the practicability of the above hypothesis to predict radiation effects in a natural oak-pine ecosystem located on Long Island.[48] Comparisons were made between predicted results with those which occurred after irradiating the ecosystem.[15] Discrepancies between anticipated and actual results indicated other influencing factors must have been operative, as the precision of estimates was less than expected. Sparrow, in discussing additional factors beside nuclear volume which influence plant response to radiation, emphasizes the need to specify the life-history stage being irradiated, i.e., pollen, embryo, seeds, seedlings, young, mature or senescent plants are differentially radiosensitive.[47] In addition, other environmental stresses, operating in conjunction with ionizing radiation and occurring before, during, and even postirradiation, have been shown to further alter plant response and are discussed later.

Though a great deal more research is needed to improve prediction reliability, particularly concerning the yields of seed-producing plants, and alterations in tolerance to disease, insects, or environmental stresses, this nuclear-volume/radiosensitivity hypothesis and the tables of data supplied by Sparrow are of enormous value in evaluating potential effects of radiation on individual plants and communities.

Modifications of the nuclear-volume/radiosensitivity concepts are being developed to predict response to radiation of plant seeds, and hopefully certain mammalian groups.[49] Also Golley, et al., in studies of radiosensitivity comparisons between laboratory and wild animals, notes that wildness per se does not confer radiation resistance, but rather that species vary in response to radiation on the basis of their physiological, ecological, and evolutionary background.[50]

Others (Myser, Ohio State Univ., personal communication) operating on the premise that radiosensitivity of hemolymph of insects may be comparable to radiosensitivity of blood in mammalian blood systems are attempting to develop a method of predicting radiosensitivity of insects.

(2) Interactions of radiation and environmental stresses.

Effects from particular radiation doses can be predicted reasonably well in laboratory or optimum-environment experiments, but wide discrepancies between anticipated and actual results may occur in field situations. This is because combinations of environmental circumstances elicit plant responses which may mask, intensify, or possibly inhibit other responses predicted from nuclear volume characteristics.[15, 21]

Researchers investigating interactions of ionizing radiation with other environmental stresses have shown that the intensity of simultaneously operative or post-irradiation environment factors may materially alter plant response to ionizing radiation.[34,35,51,52,53,54,55,56,57] Golley and others are also investigating radiation/environmental stress relations among animals.[50] Relative amounts of light, temperature and available moisture acting in conjunction with ionizing radiation seemingly can produce significantly different effects than one would expect. Thus, the universally accepted ecological principle: "whenever an organism is growing in a situation which is near the limit of its tolerance to one or more factors, its sensitivity to other factors is often increased," seems to have validity even when radiation effects are considered, and thus may well be called a radioecological principle. Though not often stated, this principle has some intrinsic considerations: (a) if an organism is growing in an optimum environment, it may withstand a greater than normal intensity of one deleterious factor before it shows an effect, and (b) if an organism is growing in an environment unfavorable for one or more factors, another factor (ordinarily deleterious) may compensate for the limiting factor -- for example, shade might compensate for soil drought.

The above principle is somewhat related to the so-called LaChateliers theorem, i.e., "an intensification of an environmental factor tends to increase an organism's resistance to further intensification of that factor." This principle seems to be true in relation to such environmental factors as drought and frost, but in regard to radiation the question would be whether or not the radiosensitivity of organisms chronically exposed to radioactivity will be increased or decreased when they are later exposed to higher levels of radiation. The existence of acquired resistance seems to be accepted in particular types of animal studies,[58] but experimental data in regard to plants are equivocal.[58,59]

(3) Life form and radiosensitivity.

Under conditions of chronic exposure to radiation, as Sparrow and Woodwell indicate, any environmental factor which slows plant development, and thus increases both irradiation time and accumulation, usually increases the radiation response.

In the case of acute exposures, no method other than Sparrow's radiosensitivity predictions of individual species, has been developed to predict radiation effects upon assemblages of plants (plant communities or ecosystems) living under natural-environmental stresses. However, Woodwell, Brayton and Woodwell have recently presented a supposition which may possibly allow gross predictions of community response to radiation to be made.[16,60] Briefly, the contention is that plants adapted to tolerate harsh environmental conditions are also more resistant to radiation damage. It would seem "...that characteristics that confer resistance to certain types of environmental extremes also confer resistance to damage by radiation." The strong parallelism between effects of fire and of radiation on a particular Long Island plant community -- huckleberry populations decline at the expense of increases of blueberries and sedges -- is offered as one example of supporting evidence.

Another example, offered by Woodwell, to substantiate the above contention is that continuous irradiation of a forest community produced a sorting by size or life form (trees, shrubs, tall herbs, prostrate plants) along the radiation gradient, smaller forms of life being generally more radiation resistant than larger ones. It was noted that this condition frequently exists in nature along gradients of increasing climatic severity, such as the transition from forest through a shrub zone to one of prostrate plants in high-altitude or high-latitude regions. This relationship between life form and radiosensitivity, and the parallels between radiation effects and effects of environmental gradients may simply be a fortuitous happenchance, if real. Nevertheless, as these relationships would help predict community response to radiation, and perhaps basic processes of life response to environment, such studies should be intensified.

Furthermore, as a number of investigators believe a strong relation exists between life form and toleration to temperature extremes during the growing season (Dahl, Agricultural College of Norway, personal communication) studies similar to those conducted by McCormick,[52] concerning temperature and ionizing radiation should be increased. In addition, studies relating radiation sensitivity of interaction with environmental- or biological-stress-producing conditions such as frost, light quality and quantity, low humidity, disease, and insect infestations, should be conducted since many research areas are essentially unexplored and may offer rich returns in being able to predict radiosensitivity of organisms under disturbed environmental conditions. Too, the idea of evolutionary history being related to radiosensitivity could be tested, i.e., comparisons of the degree of radiosensitivity (or nuclear volume) with the relative evolutionary development, or primitiveness, of vascular plant species could lead to a statistical test for a significant correlation.

HYPOTHESIS AIDING PREDICTION OF FALLOUT NUCLIDE FATES

In considering ecological damage and recovery from nuclear attack, problems regarding levels of radiation to which organisms within an ecosystem may be exposed are frequently by-passed, or only briefly contemplated. The tacit assumption is usually that all organisms will be exposed to similar levels -- i.e., radiation doses are projected upon an infinite plane. Hence, predictions of radiation damage from fallout are made largely on radiosensitivity of organisms with little or no regard to the likelihood of differential exposures to radiation. As an indication of how misleading this can be, Osburn reported the levels of gross beta radioactivity per square centimeter of ground surface in a Colorado mountain watershed varied in 1963 among plant communities within an eleven-square-mile Colorado mountain watershed from a few picocuries to well over two nanocuries, and in a limited number of exceptional situations the level of concentration approached the millicurie level.[34] In addition, due to differential fallout distribution, buds of relatively radioresistant Vaccinium plants forming the ground cover in the subalpine forest region were exposed to well over 1,000 times more fallout radioactivity than buds of the radiosensitive overstory spruce and fir trees. Thus the magnitude of radiation dose, superimposed upon the landscape and occupying biota by the pattern of fallout accumulation would in many instances certainly outweigh the influence of differential plant radiosensitivity. Hence, it is obvious that, until one can estimate the radiation doses that various organisms will receive, it is of little predictive value to know only radiosensitivity of organisms. Inability to predict possible dosages may well be our weakest link in forecasting the impact of a nuclear attack. Russell, in commenting upon the greater amount of research effort expended towards strontium-90 and cesium-137 uptake from the soil as contrasted to foliar deposition, emphasizes this weakness: "...we may regret that greater attention has not been given to those aspects of the direct contamination of plants which exert a dominant effect in many circumstances."[81]

Fallout Retention

Beginning with nuclear detonation and projected until decay reduces radioactivity to insignificance, extensive research has been conducted concerning alteration of fallout-nuclide composition. Several general models have been constructed to depict and predict these sequences.[82,83]

Research has substantiated the accuracy of some compartments of these models but many unproved sections exist. One section which is poorly known concerns relative amounts of fallout intercepted and retained by various types of natural vegetation.

In particular, mechanisms responsible for differential interception and/or retention efficiency have been studied in only a few geographical regions, under a limited number of weather sequences, and for a minimum number of vegetation types. Consequently, few guide lines for quantitatively predicting fallout concentration in natural ecosystems have been formulated. For example, the 1963 Project Harbor report arbitrarily assumed a one percent retention of fallout on plants, without considering specific lodgement sites on particular plants.[46] Romney, et al., and Martin worked in a cold desert region;[64,65,66] Rickard carried out studies in a prairie region;[67,68] Russell reported results from a region relatively high precipitation and of permanent pasture;[61] Menzel, et al. experimented with horticultural plants in a wet and in a dry region.[69] All agree that the major amount of fallout was associated with foliar deposition which, in turn, was related to total precipitation.

As Miller suggests, the contamination of foliage by fallout particles of a given diameter should depend on amount of foliage surface available for contamination, the collecting efficiency (I prefer interception-retention efficiency) of foliage surfaces for particles of different sizes and other factors, such as wind velocity during and after particle deposition.[62,70] Additional factors which should receive consideration are gross morphology of plants, phenology, length of growing season, and the amount, type and intensity of precipitation.

Osburn reporting on the fallout-interception-retention efficiency of three different alpine-tundra-plant communities in 1962 and again in 1963 noted the efficiency ranged from 30 percent to 77 percent in 1962 and in 1963 was reduced to a range of 8 percent to 21 percent.[34] Although this difference could have been related to change in fallout-particle size or changes in the productivity or morphology of the plants, the most plausible explanation concerned the difference in weather regimes between the two years (largely the amount and intensity of rainfall), and perhaps some predormancy translocation of cesium-137 in regard to the Carex vegetation.

Although such factors as stickiness or pubescence undoubtedly influences fallout entrapment on plant surfaces, perhaps the single most important factor (if fallout particles are not too large, say, less than 10 micron[64]) is the relative leaf surface per unit ground-surface area, i.e., interception is highly correlated with plant density. As plant density is a parameter frequently measured by most plant ecologists, data expressing average plant densities according to season of the year are available for many major U. S. ecosystems and should be incorporated into nuclear-attack-damage considerations.

Furthermore, great effort should be directed towards a number of heretofore rather poorly researched items. For instance, attention should be devoted towards whether meristematic regions and reproductive organs of plants tend to accumulate or dissipate fallout nuclides. It is entirely conceivable that due to position within a plant community and especially due to morphology, meristematic tissue of a relatively radio-resistant plant such as the dandelion could accumulate a level of radiation exposure proportionally greater to its resistance than a radio-sensitive plant such as a pine or spruce tree.

Although levels of atmospheric fallout are now generally too low to study efficiencies of fallout entrapment by various plants and plant parts under various weather and phenological regimes, other indirect methods of study, such as the imaginative study reported by Miller concerning foliar retention of volcanic ash,[71] could be investigated. Perhaps field plots, wind tunnel, or growth-chamber situations to test entrapment of simulated-fallout particles of known size, deposited under specific moisture or wind patterns, could be utilized. In lieu of direct experimentation, perhaps measurements of debris loads naturally accumulated by plants, and/or of the amounts of various forms and intensities of precipitation intercepted, could give, indirectly, an index of possible fallout-interception efficiency.

Nuclear Fallout and Wild Animals

Pathways of fallout contamination leading to man have been extensively examined and are reasonably well understood. Yet, concentration of fallout nuclides on or in wild animals -- exclusive of certain ungulates, such as caribou, reindeer, and mule deer -- has scarcely been considered,[72] and consequently no rules to predict contamination have been ventured. Brown, et al., indicate, however, that direct fallout deposition upon animals could be quite important.[73] Although the study of Osburn concerns high-mountain ecosystems,[34] results may well have much wider application, or at least suggest several avenues which should be examined in order to establish valid relations between wild animals and a nuclear-fallout-contaminated environment.

During the autumn months of 1962, 1963, and 1964, approximately 500 mammals and birds were collected in the Boulder, Colorado, high-mountain watershed. Most animals were sectioned into subsamples of fur or feathers, stomach, cheek, pouch, or crop contents, prefaeces, and eviscerated-skinned body. Each subsample was ashed and counted for gross beta radioactivity expressed as picocuries per unit fresh weight. A representative number of subsamples were composited and subjected to nuclide analysis.

In general, the amounts of radioactivity contained in the various body components reliably reflected the food source, behavior or habitat of the animals, regardless of their taxonomic positions. Specifically, the large differences noted in levels of radioactivity of the skin and feathers of various species of birds may be explained by the differences in behavior patterns, especially those exhibited in the search for food. For instance, the radioactivity (picocuries/gram) of the skin and feathers of the following list of birds (and one mammal) was graded according to the relative amounts of time each species tends to spend flying:

> bat, *Myotis*, sp. (846); magpie, *Pica pica* (118); goshawk, *Astur atricapillus* (66); pipit, *Anthus spinoletta* (37); sparrow hawk, *Falco sparverius* (31); and the great horned owl, *Bubo virginianus* (21).

Birds which spend a larger amount of time searching among pine needles or plants on the ground tended to encounter and retain larger amounts of fallout radioactivity. Examples are:

> red crossbills, *Loxia curvirostra* (250); chickadee, *Penthestes gambeli* (110); Clark's nutcracker, *Nucifraga columbiana* (92); Junco, *Junco canicaps* (67); and the rosy finch, *Leucosticte australis* (59).

When all vertebrate animals utilizing the Boulder city watershed were categorized by feeding habits, flesh of predators and scavengers contained relatively low levels of gross beta radioactivity, with seed-eating animals next higher, followed by grazers, and finally insectivorous animals. The extended range was well over a factor of 10.

It is of interest to note that in the case of two rodent species (pika and pocket gophers) juvenile individuals relegated to less optimum sites than were the adults contained much higher radiation burdens. Under nuclear-recovery situations, this could be a significant mechanism to retard population explosions and needs further research to determine whether this situation might apply to other species.

Research by French strongly suggests granivores ingest less radioactive material than herbivores living in the same contaminated environment because herbivore food has a much larger surface area per amount needed to sustain life.[74,75]

Though meager, the above data indicate that relative nuclide-accumulation patterns of animals vary considerably, but can be contemplated where their general ecology is known.

Food Chains and Radioecological Concentration

Efficiency of radionuclide transfer from soil to plants, plants to animals, within animals, up to and within man has deservedly received an immense amount of attention. It is quite true that examples of huge radionuclide concentrations have occurred and food-chain nuclide-concentration sequences, especially the lichen-to-caribou-to-man nuclide transfer sequence, are familiar to us all.[76] Since a volume of more than 1000 pages has recently been published,[77] and contains a number of tentative predictability rules and models of nuclide behavior, I'll pass over this category with only a mention of its importance when estimating potential ecological consequences of nuclear war. Too, excellent studies by members of the Ecology Section, Health Physics Division of the Oak Ridge National Laboratory convey hopeful portent that nuclide concentration within ecosystems will soon be predicted with reasonable accuracy.[78]

Before leaving the subject of radionuclide distribution, there should be a mention of the little-studied phenomena of radionuclide translocation within some plant species. It seems that once potassium or cesium-137 is taken into their systems various species of sedges and grasses tend to retain and increase these materials.[34,79] Towards the end of a growing season as shoots wither, both cesium and potassium are translocated to the overwintering buds. As a number of animals tend to feed upon buds, and as young, developing shoots might have relatively high cesium-137 concentrations the following spring, this area of research should be further investigated. Assuming cesium-137 would follow the same pathways within a plant as does potassium, it would be a relatively simple matter to design a research program which would enable us to anticipate the role of cesium-137 translocation in nuclide concentration predictions.

Specific Nuclide Concept

The most promising candidate for being considered as a radioecological rule is the "specific nuclide concept," (ratio of the amount of radioisotope to total isotope of the chemical element considered) as expressed by Lowman.[80] Briefly stated, the distribution patterns of artificially introduced radionuclides can be predicted by obtaining qualitative and quantitative information regarding the distribution of stable elements. While this concept is essentially untested in terrestrial ecosystems, it appears to have validity for marine situations. If this proves reliable it will give us an extremely valuable predicting tool.

Conclusion and Recommendations

Studies of ecosystems subjected to lethal levels of ionizing radiation -- from nuclear testing, or from multicurie gamma sources placed within natural areas -- indicate ecological recovery follows pathways of succession which are predictable and quite similar to those following recovery from other catastrophic events such as recovery from fire. In order to test the universality of this concept of recovery, additional ecosystems representative of major areas of the United States should be tested.

Since recovery from nuclear war would be expected to follow normal successional trends, accuracy of forecasting ecological recovery could be materially improved by incorporating what ecologists have thus far learned. In fact, nearly all individuals attempting to forecast specific ecological effects or recovery from nuclear warfare have stressed the availability of methods and materials to improve prediction reliability.

Perhaps the weakest link in our ability to anticipate ecological consequences of fallout radioactivity concerns differential exposure of various organisms to initial and subsequent fallout-nuclide distribution. Research has demonstrated, at least for particular landscape units, that environmental factors responsible for vegetational differentiation are operative (highly correlated) in determining the deposition and distribution of radioactive fallout.[33] As these units (plant communities) have been extensively studied and are relatively stable, they should be functional units to study for predicting ecological recovery. Though the selection of an optimum-sized unit to work out ecological consequences (e.g., likely patterns of fallout deposition, fire, erosion, plant and animal invasion, succession, etc.) will be somewhat arbitrary, the unit should have sufficient homogeneity so that data researched from one segment, particularly concerning radionuclide distribution or effects, will be valid throughout. Though many parameters which are quite important for radioecological considerations are routinely measured in ecological studies, estimating ecological recovery from nuclear war could be improved by including other parameters such as estimating surface area of plants so that an index of their efficiency to intercept and retain fallout materials could be calculated.

The United States has been variously divided into landscape regions, from five to well over a hundred units. Kuchler has prepared a detailed map of potential vegetation types of 116 units for the conterminous U. S.,[24] and it is recommended that these units be given a trial as the basic-sized unit to use for predicting ecological consequences. It may be that many of the units will not differ significantly from one another as far as influencing fallout distribution patterns, nor in influencing radiation damage and recovery and can later be composited, or perhaps in some cases further divided.

As the International Biological Program plans to analyze major U. S. biomes (grasslands, conifer forests, deciduous forests, tundra, deserts, and a tropical region) in some detail[6] it would benefit ecological-recovery prognosticators considerably if the parameters measured could be increased so that all presently known important parameters for making valid forecasts of recovery could be included. These additions might well be estimates of the size and composition of annual and cumulative plant-seed "rains," plant regenerative capability after fire or erosion, indexes of debris or fallout-particle interception and retention, terrain shielding, concentration of water in relation to the morphology of reproductive organs of various organisms. Also of importance is ecosystem heterogeneity (diversity of topography, soils, vegetation, fauna, etc.). These factors influence initial damage upon an ecosystem from fire, flood, wind, etc., and thus play a significant role in the rate of ecosystem recovery.

As far as I know, no landscape unit has received a study of sufficient detail that the investigators will confidently predict the degree of damage a nuclear catastrophe might effect--initially or upon a long-term basis. However, studies of the Cape Thompson region in Alaska, of ecosystems at the Oak Ridge and perhaps the Brookhaven National Laboratories, and of the Battelle-Northwest and Savannah River ecology groups, as well as my own mountain-watershed study, are reasonably complete and perhaps if a researcher wished, a "radio-ecological survey manual" could be prepared which would represent the most accurate forecasts (including error in estimating) we could presently make regarding long-term ecological recovery from nuclear war. This manual could then serve as a guide for similar compilations in other regions of the United States. Certainly it seems reasonable that a guide to expected damages and expected recovery would be a worthwhile advance preparation, since even local effects of a nuclear war would be catastrophic to those involved.

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Summary

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The kinds of effects described and discussed here are not individually unique to nuclear catastrophes; most can and do result from a variety of nonnuclear forces commonplace in our biosphere. What would be unique about a large-scale nuclear catastrophe stems from (1) the interaction of several severe limiting factors, with total effect not simply the sum of component effects, and (2) the great size of the stressed area, a quantity probably influencing the rate of recovery more than the severity of the acute forces themselves.

As the writers of this symposium so ably documented their specific topics I jotted down some of the ecological sequelae of storms, forest fires, pest irruptions, gamma irradiations, and other natural, accidental, or experimental stresses that mimic, in one way or another, nuclear war. From the standpoint of the ecosystem as a whole any acute limiting force, whether nuclear or not, might have some or all of the following consequences.

1. *Reduction in biological structure* (standing crop biomass). Storms, fire, and bulldozers, as well as the blast component of nuclear explosions, remove protective living matter from the landscape. As a consequence, temperature and moisture fluctuations may increase and nutrient loss may accompany the erosion of substrate. The damage that results from the sudden removal of protective vegetation varies greatly in different ecosystems depending on how well the physical structure of the environment is able to resist weathering in the temporary absence of, or reduction in, biological structure. Man should have plenty of information to predict the outcome of biomass removal because he has had centuries of experience in doing so!

2. *Growth inhibition* and reduction in productivity. These can be the result of frost, drought, etc., as well as ionizing radiation. Observations in Dr. Platt's irradiated forest indicate that an acute dose of ionizing radiation differs from an acute dose of frost chiefly in that growth inhibition continues for a longer period of time after the former stress. Despite the dramatic observations that have been made, quantitative data on (1) the actual reduction in rates of primary production (in terms of calories per unit time per unit area) and on (2) the recovery time to be expected at different dose levels in different ecosystems are almost completely lacking for the kind of single acute doses to be expected in nuclear catastrophes.

3. *Differential kill.* Since living components of ecosystems differ widely in sensitivity and vulnerability to different limiting factors, selective kill is a common result of weather extremes, herbicides, and insecticides, as well as ionizing radiation and other components of nuclear weapons. Principles for predicting the effects of radiation on higher plants, and on whole vegetations, are emerging as a result of the pioneer work at Brookhaven as reported by Woodwell and Sparrow. Experimental data are still needed on effects of differential kill at the ecosystem level, especially in

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Odum, E. P. 1965. Summary. pp. 69-72. In: Ecological Effects of Nuclear War. (G. M. Woodwell, ed.). Brookhaven Natl. Lab., U.S. AEC report BNL-917(C-43).

aquatic, tropical, and grassland communities. The effects of different dose rates and the differences between acute and chronic doses, contingencies now being understood at the organism level, are virtual unknowns at the ecosystem level of organization. The thinking here, of course, should not be confined to ionizing radiation, since man is now intent on creating a kind of chemical "fallout" throughout the biosphere for which there is as yet no "test ban."

4. *Food chain disruption* (disturbance or failure of biological regulation). Periodic failure of biological control mechanisms is a "normal" characteristic of some ecosystems, as exemplified by budworm irruptions in northern spruce forests as described in Macdonald's paper. In general, such periodic breakdowns seem to be characteristic of ecosystems which, for one reason or another, lack diversity in their biological structure and function. Since any severe stress will not only reduce diversity but will also reduce growth and hamper plant and animal defense mechanisms, we can confidently expect insect or other "pest" irruptions to follow catastrophes, in at least some cases. As was well pointed out by Macdonald, the time in the seasonal cycle that stresses or countermeasures are applied is extremely important. Man should be better prepared to assist ecosystems in regaining homeostatic control, since nature is wonderfully resilient if not stripped of the self-regulating mechanisms inherent in the natural diversity of predators and parasites. Thus, a healthy, diversified landscape can be expected to recover from severe stress better than a landscape that is already "sick" and overstressed by man. Unfortunately, the success of insecticides in agriculture has given man a sense of false security in regard to pest control in all environments. The net result has been that the study of life histories and food chains, once respectable research areas for the naturalist-oriented ecologist, is considered passé by the laboratory-oriented biologists of today. In the meanwhile wholesale destruction without understanding replaces scientific research in the field. The threat of a nuclear war should shock us out of the "one-track" approach, since the spray gun probably will not be so available after a catastrophe (or, in the opinion of many, the unrestricted use of the spray gun will eventually lead to a biological catastrophe, war or no war!).

5. *Succession setback.* Long and complex ecological successions are especially characteristic of terrestrial ecosystems, a fact often overlooked by the physical scientist because succession is strictly a biological phenomenon (that is, while the physical environment determines the pattern of successional stages it does not cause succession to take place). Any severe stress has the tendency to set back succession to an earlier or "younger" stage. Such setbacks are, of course, not necessarily bad. Man uses fire to revert succession from a less productive to a more productive stage (from man's standpoint). Practically all agriculture involves maintaining "youthful" types of communities which yield large, harvestable net productions. What might be critical in a nuclear catastrophe, aside from the contamination of food supplies, is a sudden and widespread succession setback in mature vegetation that functions to protect or stabilize the landscape, for example, forests on steep slopes. Since the early stages of succession are less stable than the mature stages, the stability of the whole landscape would be reduced as the proportion of young vegetation increased, which would increase the probability of both physical and biological breakdowns as described in the preceding paragraphs.

6. *Changes in nutrient cycling rates.* The impact of severe stresses on nutrient cycles vital to the maintenance of productivity is but little understood at present. Sometimes disturbances make nutrients more available (as is the case, for example, in disking a sod-bound pasture or upwelling the bottom waters of a lake) and are followed by "blooms" in productivity; in other cases nutrients are lost from the biologically available pool. Radionuclide tracers inadvertently introduced into the biosphere via fallout from weapons tests offer an overlooked opportunity for experiment. As the movement of these tracers becomes known in a given ecosystem, one could subject the system to severe stress (fire, for example) and observe the resultant effect on the movement of tracers. Experiments such as the "cesium-137 forest" at Oak Ridge represent another approach that should provide answers.

7. *Evolutionary changes.* The past history of the biosphere indicates that catastrophes often result in marked changes in flora and fauna as a result of increased mutation rates, extinctions and invasions, removal of barriers, changes in competitive relationships, and the other evolutionary processes that are accelerated by mass destruction. A "postclimax" forest, for example, if destroyed or badly stressed would almost certainly be replaced by a different forest. The presence of mutagenic agents in the fallout accompanying a nuclear catastrophe might increase the mutation rate, change the selective pressure and, therefore, increase the probability that the recovered ecosystem would not be in exactly the same state as before the catastrophe.

Now that several broad *consequentiae* have been listed, let us return to the generalization in the first paragraph of this summary. My major point is that we already have considerable experience with, and some understanding of, the consequences of most of the individual factors that would result from a nuclear catastrophe. For example, a great deal is known about fire in the environment as documented in Dr. Broido's excellent summation. Thus, we can predict fairly well what will burn at a given time and place as a result of the "million-lighted-match" effect of thermal radiation from a nuclear explosion. While we should push ahead in the study of these individual factors, the greatest unknown stems from our almost complete lack of experience and understanding of *the interaction of factors that would be unique in a nuclear catastrophe.* Furthermore, radioactive fallout adds an additional dimension that is new to the biosphere; it is the one factor unique to nuclear force, and one that we have had but 15 years to study in a scientific manner!

The interaction of fallout and fire can be taken as an example. Since all nuclear tests have been conducted in essentially incombustible environments, there are no experimental data to indicate how these factors would interact. They could very well cancel rather than augment one another, in terms of total effect on man's environment. It is now well known that fallout nuclides enter the food chain of man and animals much more readily as a result of direct foliar contamination of vegetation than as a result of uptake from the soil. Consequently, the hazard would actually be reduced if the vegetation were burned just after or during fallout, because the fallout nuclides would end up in the soil rather than on the leaves. New plant growth would be far less contaminated than the original vegetation. The shielding capacity of mineral soil could also reduce dose. It might even be desirable to burn badly contaminated vegetation or crops as a recovery measure.

The interaction of fallout and fire could easily be subjected to experimental test. In fact, I am tempted to design such an experiment in connection with the ecological studies at the AEC's Savannah River Plant! A bit of artificial fallout could be laid down on one of the well-studied old-field or grassland ecosystems, and the vegetation then burned off on part of the area so as to provide a direct comparison. Experiments of this sort might also settle some of the questions that have been raised concerning the effect of fire on nutrient cycling.

The other great unknown hinges on what might be called the "mass effect." As the number of acres destroyed or stressed increased, the recovery time for any one acre would likely increase greatly. A small area, even if severely affected, remains protected by, and can be quickly repopulated from, the surrounding unaffected or less affected areas. Experience with the unshielded reactor at Dawsonville, Georgia, provides a good example. After one of the high-energy runs the entire population of marked cotton rats living in the adjacent small field was exterminated, but repopulation by unmarked migrants occurred rapidly. Small birds entering the radiation field were also undoubtedly killed, but repopulation was so rapid that "before and after" censuses revealed no clear-cut total effect. If a radiation field of exactly the same intensity had extended over thousands of acres the situation would be quite different; "before and after" censuses would show marked differences, and recovery would require much more time. Unless man was able to provide seeds and animal stocks to devastated areas of the size pictured by Dr. Miller in the opening paper, years might be required for repopulation. It is even possible that species with restricted geographic ranges would be completely exterminated. Small-scale experiments are not of much help in evaluating "mass effect." Comparison of recovery following the very large forest fires as mentioned by Dr. Broido and recovery following small, local fires of equal intensity might provide a basis for determining what power function should be used in relating recovery time to size of affected area.

Disposal of Radioactive Wastes in Fresh Water

By F. L. Parker

Progress toward the solution of problems of discharge of radioactive waste into fresh-water systems has been more rapid since the subject was last reviewed in a previous issue of *Nuclear Safety*[44] than in all the years since the practice began in 1944. Reviews of the minutes of the AEC Working Meeting on the Transport of Radionuclides in Fresh-Water Systems[45] and recent Canadian,[46] English,[47] French,[48] and Russian[49] literature support this assertion. Basic to this outlook is the separation of river problems into those caused by large-scale producers or users of radionuclides and those resulting from small-scale uses of nuclides. A fundamental aspect of this distinction is the view that the only method of assessing pollution is the degree of harm to man or his environment. By this criterion it is postulated that small-scale users cannot usually cause damage to man or his environment. Another equally important distinction is between operational or applied research and basic research. However, although all big producers must do some applied research, few do the basic work necessary to advance the understanding of the complex phenomena occurring in a natural river system.

Represented at the AEC meeting were the Oak Ridge National Laboratory (ORNL) and Hanford Atomic Products Operation (HAPO), as well as the universities and major governmental agencies concerned, i.e., the Public Health Service and the Geological Survey, in addition to AEC. The most significant of the applied research papers were those presented by Oak Ridge and Hanford representatives.[50–53]

Clinch River Study

The Oak Ridge papers discussed the comprehensive, cooperative study of the Clinch River made by the Waste Disposal Research, Ecology, and Applied Health Physics Sections of the Health Physics Division of Oak Ridge National Laboratory, U. S. Geological Survey, Tennessee Valley Authority, U. S. Public Health Service, Tennessee Game and Fish Commission, Tennessee State Department of Public Health and Stream Pollution Control Board, and the U. S. Atomic Energy Commission.[54–57] Following its formation in February 1960, the steering committee for the study established five basic objectives:

1. To determine the fate of radioactive materials currently being discharged to the Clinch River
2. To determine and understand the mechanisms of dispersion of radionuclides released to the river
3. To evaluate the direct and indirect hazards of current disposal practices in the river
4. To evaluate the overall usefulness of this river for radioactive waste-disposal purposes
5. To recommend long-term monitoring procedures

In order to accomplish these objectives, four subcommittees were established to manage the research efforts in the various fields, and a study coordinator was appointed to assure the total integration of effort. The work of the various subcommittees is summarized briefly below.

1. *Bottom Sediment Sampling and Analysis.* The committee initially reviewed all the available data on bottom surface sampling and radiation[58,59] and quickly realized that a more intensive sampling effort was required. Consequently in 1960, cores were taken from the bottom of the Clinch River with a Pfleger type sampler, and a nuclide inventory was obtained which estimated the total amount of nuclides in the Clinch River sediments as 75 curies. Because the sampler was only 2 ft long, it was felt that the depth of the entire radioactive zone was not penetrated, and, consequently, in 1962, sediment samples were taken through the entire contaminated zone on the Clinch River and on its tributaries using a Swedish foil sampler.[60] The inventory is still being determined, but it has been estimated[61] that the total retained load will not exceed 300 curies, out of a total of 12,000 curies discharged to the river since 1944 (Ref. 50). The subcommittee has also determined that sloughs do not have a heavier buildup of radionuclides than the main river, that there is a longitudinal dispersion of the radionuclides in the sediment, and that the radiation from the sediment depends on the previous years' release of radionuclides from the laboratory. In addition, more basic studies on the sorption and desorption of the radionuclides from the bottom sediment[62] and

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Parker, F. L. 1964. Disposal of radioactive wastes in fresh water. Nuclear Safety 6(1):89-94;96-97.

the complex mechanisms by which the nuclides are deposited on the bottom or remain in solution have been carried out. Here, "*remain-in-solution*" is taken to include all particles less than 0.7 μ.

2. *Water Sampling and Analysis.* An extensive network of continuous proportional sampling stations upstream and downstream of the confluence of White Oak Creek with the Clinch River, the sole point of discharge of radioactive waste from the laboratory, was established to measure the total flux of activity past each station.[63] Results from the first year of study indicate that the four most hazardous nuclides in the Clinch River, ^{90}Sr, ^{137}Cs, ^{106}Ru, and ^{60}Co, have essentially passed undiminished out of the Clinch River. This indicates that the biota and bottom sediment are not retaining a large amount of the nuclides discharged to the river.

3. *Aquatic Biology.* Extensive sampling of the sight and bottom feeders in the Clinch and Tennessee Rivers was undertaken to determine the size of this potential reservoir of activity. In addition a specialized laboratory study on the modes of uptake and the concentration factors of specific species of fish was carried out. The average flesh contamination of bottom feeders was estimated to be 420 $\mu\mu$c/kg and of sight feeders, 540 $\mu\mu$c/kg.[64]

4. *Safety Evaluation.* The data developed by other subcommittees were supplied to the Subcommittee on Safety Evaluations for determination of the dosages received by both "standard man" and specialized members of the population because of ingestion of water, fish, and irrigated crops; swimming; nearness to contaminated sediment in the river; and nearness to components of water-treatment plants using contaminated river water as a source of supply.[65,66] These investigations did not disclose any presently significant hazards from the release of radionuclides at the Laboratory.

Possibly the most important outcome of the Clinch River study to date has been the successful application of mass-balance techniques to the entire river complex. Having shown that the waterborne load was almost the entire amount discharged to the river and that the bottom-sediment load was small, the study then showed that the maximum inventory possible in the biomass was exceedingly small and could be neglected.[51] Soviet scientists have reached the same conclusion, even with stagnant lake conditions, which ordinarily would be considered to favor higher inventory of radionuclides in the biomass.[49]

The study illustrates in the most graphic fashion the steps required for a comprehensive analysis of a river system receiving radioactive wastes. First, an overall plan of study is required,[67] then suitable personnel and funds to carry out the study, and, finally, a broadly based steering committee to evaluate the progress and suggest new areas of study on a current basis. Careful review of the status reports will give those interested in undertaking such a study a model to follow.

IAEA Recommendations

A description of a more general model for such studies was recently issued by the International Atomic Energy Agency (IAEA) under the title "Disposal of Radioactive Wastes into Fresh Waters."[68] The report, a result of the deliberations of a panel of highly qualified experts, is of little help in planning a program, however, because it is couched in general terms. It is useful, nevertheless, for administrators and the general scientific public in that it points out the problems to be considered in making such a study. The purpose of the report is "to present the principles and practices of radioactive waste management which will ensure that the use of fresh water systems will in no way be jeopardized." The report asserts truisms on freshwater systems and the mechanisms that control the distribution of introduced pollutants in 17 pages, whereas Hutchinson required 1015 pages to cover only the geography, physics, and chemistry of lakes.[69] Small sections of the report[68] also cover, in general terms, radiation exposure from the disposal of radioactive wastes into fresh water, waste-disposal site considerations, and, perhaps most interestingly of all, legal, administrative, and organization principles of radioactive waste pollution control. It recommends that a national government discharging waste in fresh water within the borders of its own country "can completely determine the details of such disposal provided: (*a*) the disposal should be carried out in such a manner that detrimental effects will not be felt in marine waters and (*b*) such disposal should not give rise to any deleterious effects outside the borders of the country." For international fresh water the report recommended establishment of special bodies for particular drainage basins by bilateral or multilateral conventions "to lay down conditions governing the discharge of wastes into international fresh waters by each of these countries." The implementation could be carried out by the governmental parties to the convention, or the special bodies could also be the administrators of the conventions.

The second part of the panel report is primarily a condensation of three review papers on radioactive wastes presented in behalf of the Agency to UNSCEAR in March 1961 (Refs. 70–72), Parker's list of the main transfer mechanisms of released waste presented before the U. S. Congress at the Hearings on Industrial Radioactive Waste Disposal,[73] and sample calculations for radiation dose determination. It is unfortunate that the Agency did not see fit to include a condensed version of the fourth review paper presented in their behalf to the UNSCEAR Committee.[74] This paper gave a perspective on the relative environmental hazards in freshwater systems from radioactive waste disposal.

It should again be clearly pointed out that the research discussed above and in the IAEA report refers primarily to large-scale handlers of radioactive materials, such as a fuel-element processing center or a large atomic energy establishment. This research, although applicable to understanding the processes that occur in a river system, has little bearing on the commercial nuclear power reactor with a closed-cycle coolant. For example, HAPO releases about 2000 curies/day, primarily short-lived activation products, to the Columbia River; ONRL releases vary widely and have been as high as 6.1 curies/day, but in 1963 they were 1.3 curies/day; the Yankee reactor released only 0.6 μc/day in 1961 and 1962; and Shippingport released only 0.1 mc/day in 1958 and 1959 (Ref. 75).*

Studies of River Sediment

At the AEC meeting, Nielsen[52] of Hanford pointed out the major effect the physical form of the nuclide may have on its subsequent history. For example, most nuclides introduced to a water system as particles remain particles, no matter what the chemical form. Some preliminary attempts were made to obtain mass balances of the nuclides injected in the Columbia River, but, as Foster[53] cautions, "all the concentrations are continuously changing and the sizes of the diagrams (total concentration) are also changing," and therefore the mass-balance relations determined on the basis of a series of short-term tests may not be truly representative. Continuous proportional sampling to obtain data for mass-balance studies is now under way. Although there is virtually no sediment in the river down to the reservoir behind McNary Dam, substantial quantities of nuclides have been depleted in that stretch of the river. Nielsen points out that, if it is assumed that the bottom sediment is the reservoir for the missing nuclides, one should find some indication of this in the suspended sediments. Measurements of the suspended and dissolved solids, however, indicated that only 1% of the ^{24}Na was on the filterable solids, but 50% of the ^{24}Na, excluding decay, was lost prior to passing Pasco, upstream from McNary Dam. Hall and Wilson, also of Hanford, have previously evaluated the effects of discharging radioactive wastes into the Columbia River and concluded that a few people who eat unusually large amounts of fish may acquire about 30% of permissible exposure values to the bone and that water drinkers at Pasco and Kennewick received about 5% of the permissible exposure value to the gastrointestinal tract.[76] The schedule of environmental sampling is also given in the paper,[76] which may be a useful guide to setting up other sampling schedules.

Typical of the university type of basic research is the work of Odum,[77] wherein he tries to relate minor elements in waste to carbon (the most abundant isotope in the metabolic processes). There is an attempt to relate the rates of minor elements to carbon metabolism and thereby predict cycles of the minor elements. Odum tries to formulate these biogeochemical circuits as electrical networks. Although there has been some success in using this method, still more data are needed on each of the systems, and it is necessary to test their correlation under both steady-state and transient conditions.

Two interesting papers from the Geological Survey[78,79] deal with the relation of sediment to river quality and movement of radionuclides. Kennedy[78] has examined a variety of eastern and western streams and notes that, in general, the exchange capacity of the sediment in streams rises as one goes west and the ratios of adsorbed cations to dissolve cations is more constant than either one alone. He also points out how much more important bottom sediment is than suspended sediment in buffering river water by showing that small depths of sediment are equivalent to the exchange capacity of suspended sediment. Organic matter was included as part of the bottom sediment. He feels that more research is required on less pure clay mixtures, the amount and role of the organic material in the bottom sediment, including the exchange capacity, and the depth of interaction of stream water with the bottom sediment. Sayre and Hubbell[79] have devised a Lagrangian system to describe bed sediment movement, but they require more data on the mean length of the sediment particle travel and the mean rest time between each travel. These are determined from the integrated values obtained from the rate of movement of the mode of the pulse of tagged sediment and the rate of attenuation of the peak concentration with respect to time. Sayre and his associates had previously done a literature search on the uptake and transport of radionuclides by stream sediment which is a good introduction to the topic.[80]

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*These release-rate data do not include tritium release.

Tamura and Bonner[62] have shown, for Clinch River sediment, that cesium is barely desorbed under any conditions, that in up to $1M$ salt solutions between pH 6 and 8 less than 10% of the ^{60}Co and ^{106}Ru are removed, and that 30 to 77% of the ^{90}Sr is removed, depending on concentration and pH. In strongly acidic systems, up to 80% of the cobalt and up to 90% of the ^{90}Sr are desorbed, but little ^{106}Ru. In strongly alkaline systems, about 15% of the ^{60}Co is desorbed and up to 47% of the ^{106}Ru, but little ^{90}Sr. More contaminated upstream sediment was used, and the tests showed that about 50% of the ^{90}Sr in the sediment is associated with $CaCO_3$.

Nelson,[81] in addition to determining the movement of sediment downstream by tubificid worms, which was insignificant, also measured the amount of chironomid production (as high as 20 g/m^2 per year) and determined that the chironomid could remove as much as 3.5×10^{-5} μc/m^2 per year of the ^{90}Sr, which is equivalent to $^1/_{45}$ of the fallout rate.

System Analyses of River Pollution

Spofford and Thomas[82] presented a paper on system analysis as applied to pollution in a river. Since the same approach was amplified and presented elsewhere by Thomas,[83] the discussion here is based on both the recent monograph and a recent book.[84] Thomas summarizes the work that has been going on at Harvard over the last 10 years and classifies streams into four categories, based on the flashiness of the flow and uptake of radionuclides by bottom sediment. Flashiness is determined by the ratios of the average monthly flow in the stream during the month of greatest average runoff to the average monthly flow in the stream during the month of least average runoff. The critical value is 10. For regulated streams the ratio can be expected to be less than 10, and it is assumed that the magnitude of the 5- or 10-year flood is not great enough to completely scour the stream bed, so activity buildup in the bottom sediment can occur. Thomas also assumes that, for streams with a fixed maximum-minimum flow ratio, absorption and uptake are proportional to the area of contact of water with solid surfaces. The most general function of area of contact relative to the volume of water is the hydraulic radius. Ten feet is assumed to be a convenient point for separation.

Other investigators would point out, as was done in the Texas meeting, that the type of bottom and sediment composition are far more important than area of contact alone. On the basis of Thomas's classes, stream flow, and geometric parameters, it could be stated, for small or large streams, whether they would have a high or low absorptive capacity and whether there would be effective or sluggish flushing of the bottom sediment. For a random distribution of floods and the average proportion of waste being sorbed on the stream bed during the time period in which no flood occurs, Thomas was able to show in a simple statistical analysis that both the average amount of activity stored in the bottom sediment and the standard deviation of the activity could vary widely.

Thomas progressed to more sophisticated analyses, taking into account social, economic, and public health aspects of other uses of water resources through the use of game theory, probability theory, linear programming, dynamic programming, and digital-computer simulation. A simplified deterministic model was established to show the theoretical principles involved. Basic to the system is the establishment of an objective such as a physical constraint limiting the amount of radionuclides released or an economic restraint. Through the use of Lagrangian undetermined multipliers, it is possible with an economic restraint to determine the most economic expenditure of funds to meet the desired technical criteria. This is the problem-solving part of system analysis, but, even more importantly, system analysis can be used as a problem identification tool to rank system parameters in order of relative importance to the total cost of the project and, ultimately, the optimum allocation of research funds. The last item is based on having some formulation of the return for each research dollar, which is highly unlikely. This is the first known use of system analysis in radioactive waste-disposal problems, and, with the application of this method to the Clinch River study (by agreement between the Clinch River Steering Committee and Professor Thomas), a new era in stream pollution investigations seems to be opening.

USE OF TRACERS

Tracer studies can be very useful, both in models and in the river, in determining time of travel, transverse mixing, and longitudinal dispersion. However, although an ideal dye is more conservative than a radionuclide, i.e., the dye is not affected by chemical, physical, or biological mechanisms, there are differences in behavior. Tracer studies should be undertaken with caution, particularly if the nature of the tracer is not perfectly understood.

A recent study of dyes[85] has shown that fluorescein, rhodamine B, and Pontacyl Pink B can all be successfully used. Taking cost and efficiency into account, Pontacyl Pink B appears to be best for river work. Merritt's dye studies[86] can only be used as an indication of what will occur in the Ottawa River at a particular point, since part of the dye was held in storage in the deeper part of the river behind a sill, apparently because of temperature-induced density differences or density differences due to the addition of the dye.

A recent symposium, sponsored by IAEA, gives the results of the use of radioactive tracers in hydrologic studies.[87] Favored radioactive tracers for hydraulic work appear to be ^{3}H, ^{131}I, ^{124}Sb (with EDTA), ^{85}Sr, ^{51}Cr (with EDTA), ^{14}C, ^{90}Sr, ^{24}Na, ^{198}Au, ^{60}Co, and ^{106}Ru.

Foreign Studies of Waste Balances

Canadian work presented at the First National Symposium for Radioecology[88] has been briefly summarized by Ophel.[89] He shows that 75% of the strontium entering Perch Lake leaves it and that the bottom sediment contains over 90% of the nuclide remaining behind. These studies add credence to the generalizations obtained in the Clinch River studies. It is also interesting to note that the concentration of ^{90}Sr in fish flesh relative to that in water is only 5. Nelson has indicated a 1-to-1 relation if care is taken to sample only flesh.[90]

Further Canadian work is reported by Guthrie and Merritt.[46,86,91] Guthrie shows that for 1960 there is no significant difference in the amount of ^{90}Sr upstream from Chalk River (0.8 + 0.12 $\mu\mu$c/liter) and downstream (0.58 ± 0.11 $\mu\mu$c/liter).[91] He also indicates that the amount of ^{137}Cs and ^{90}Sr in the river remains essentially constant downstream, at least for a distance of 19 miles.

English research on the movement of nuclides in the Thames as a result of discharges from Harwell, Aldermaston, and Amersham is apparently on a par with work done in the United States.[47] Cesium-137 is approximately 60 to 70% of the total activity discharged by Harwell, with a cumulative total to 1960 of 37 curies out of a total of 56 curies. If the 1960 percentages held in previous years, a total of 3.8 curies of ^{90}Sr has been released into the Thames. It is estimated that about 1 curie of ^{137}Cs is in the bottom sediment in the first 25 miles downstream. The major portion of the activity was in the top 1 in. of the sediment, and the major portion of that was sorbed on the clay fraction. The cesium content of fish flesh was as high as 18 $\mu\mu$c/g. The average ^{137}Cs and ^{90}Sr contents at the point of injection into the river, assuming uniform mixing, are 15 $\mu\mu$c/liter ^{137}Cs and 0.6 $\mu\mu$c/liter ^{90}Sr, which are equivalent to about 2% of the permissible dose to the bone for the population [$^{1}/_{30}$ of the MPC occupation (ICRP)].

The French have discussed their discharges from Marcoule into the Rhone, and, although they do measure specific nuclides through gamma scans, they have presented their release data solely in terms of alpha, beta, gamma, ^{90}Sr, ^{89}Sr, and plutonium. The total release of 7.1 curies of ^{90}Sr into an average flow of 76,000 cfs makes the concentration far below MPC levels. They have sampled downstream for $6\frac{1}{2}$ miles and found no great decrease in activity in that distance. They have found an apparent discrepancy between the calculated input and the measured values which is due in part to the variability in sampling and the low concentrations measured. There are no measurements given of the activity content of the sediment or fish.

Although literature from the Soviet Union is sparse on discharges to the environment, enough research papers are available to indicate that disposal to the environment is under study or being practiced in the Soviet Union. In an interesting paper, Agre and Korogodin[49] postulate, on the basis of work done in the Soviet Union, that the biomass may be neglected as a depot of activity in a reservoir, although as a rule of thumb it can be assumed that there is a thousandfold average concentration of all nuclides in the biomass and that the bottom sediment has an average concentration a hundredfold greater than the water concentration. It is also further assumed that the bottom sediment is 4 to 8 in. thick. On the basis of these general values and a concentration of 10^{-7} curies/liter (which does not disturb the activity of its biological components) in the water, the capacity of a lake to contain radioactive materials can be determined either on an emergency or chronic basis.

Regulations and Disposal Practice

One facet of the problem which has been neglected in the discussion thus far is the effect of a change in regulations of current disposal practices. In the United States, Assistant Secretary of the Department of Health, Education, and Welfare, Quigley, has said that philosophically it is now the policy of the government to ignore the assimilative capacity of streams in determining allowable industrial waste releases, even though it is recognized that such capacity exists.[92] Quigley also stated that they intend "to administer the policy in a sane and reasonable fashion."[92] A strict interpretation of this policy could have far-reaching consequences for some of the plants now operating.

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Disposal of Low-Level Radioactive Wastes[*] into the Oceans

By F. L. Parker

Abstract: Disposal of low-level radioactive wastes into the oceans is increasing, but to date such disposals are negligible in comparison with fallout in the ocean. Internal doses to populations have limited discharge in some cases, but external doses have also limited the discharges from other sites. The effect of such discharges on the biota has not yet been resolved.

With the holding of an international symposium on the Disposal of Radioactive Wastes into Seas, Oceans, and Surface Waters,[1] the publication of a comprehensive review of radioactive isotopes in the marine environment,[2] and the publication of selected Soviet documents on radioactive contamination of the sea,[3] it appears to be worthwhile to update the previous review[4] of low-level radioactive waste disposal into the ocean. This review is restricted to low-level radioactive waste (e.g., decontamination waters and cooling waters) since high-level radioactive wastes (e.g., first-cycle wastes from the chemical processing of fuel elements) are not discharged to the environment. [For a fuller discussion of various categories of wastes, see *Nuclear Safety*, 6(4): 433-436 (Summer 1965), United States and Soviet Union Waste Disposal, by F. L. Parker.]

There are five basic questions of interest in consideration of the status and effects of the disposal of radioactive contaminated waste into the ocean: (1) Is the concentration of radionuclides in the ocean increasing? (2) Is the purposeful discharge of radioactive wastes to the oceans increasing? (3) What is the external dose to humans from radionuclides in the ocean? (4) What is the dose to humans from seafood products? (5) What is the effect of the introduced nuclides on the ocean flora and fauna? Each of these questions is discussed below, although the answers are sometimes clouded by the continued controversy between Soviet and Western scientists on the disposal of radioactive wastes, as well as on the definition of radioactive wastes.[5]

Is the Concentration of Radionuclides in the Ocean Increasing?

We can say definitely that the large-scale fallout in 1962 to 1964, due primarily to the Russian underwater and atmospheric testing in 1961 and 1962, as well as the 1962 U. S. atmospheric testing, increased the average content of radionuclides in the ocean. The Russian underwater tests during this period also increased the average content of radionuclides in the ocean. Although the concentration in surface waters of the oceans is now decreasing, the total content of radionuclides in the ocean has increased. Representative numbers for ^{90}Sr deposition and concentration are given in Table 1, which was taken from Ref. 6.

The fallout from the Chinese and French tests is negligible in comparison with the Russian and American contributions. The concentration of ^{90}Sr in Northern Pacific surface waters in 1960 to 1961 was three times that of North Atlantic surface waters. It is estimated that at the beginning of 1966 about 0.80 megacurie of ^{90}Sr still remained in the stratosphere.[7]

Table 1 WORLDWIDE DEPOSITION OF ^{90}Sr

Year	Annual deposition, megacuries	Cumulative* deposition, megacuries	Average concentration in North Atlantic surface water, pc/liter
1957		2.0	
1958	0.90	2.84	
1959	1.13	3.89	
1960	0.38	4.17	0.07
1961	0.46	4.52	
1962	1.53	5.93	0.10
1963	2.59	8.35	0.15
1964	1.84	9.95	0.18
1965	1.0	10.7	0.14†

*Corrected for radioactive decay.
†For first 6 months of 1965 only.

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[*] Editor's Note: Recent practice in the nuclear community has been to use the expression "waste contaminated with radioactivity" to describe the type of low-level waste discussed here.

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Is the Purposeful Discharge of Radioactive Wastes into the Ocean Increasing?

There is apparently no controversy about the fact that the discharge of wastes to the oceans is increasing. Furthermore, the number of installations discharging wastes directly to the seas is also increasing, as reported at the International Atomic Energy Agency (IAEA) symposium on the Disposal of Radioactive Waste into the Seas, Oceans, and Surface Waters.[1] The British report that they will discharge wastes from five civilian nuclear power stations to the sea[8] (Sizewell, Bradwell, Dungeness, Hinkley Point, and Berkeley). The amounts of discharges are based on keeping the dose as low as possible and, in any case, below the International Commission on Radiological Protection (ICRP) recommendations for members of the public living in the vicinity of nuclear installations and below an average dose of 1 rad per 30 years for the entire population of the country.[9] The allowable discharges from stations are order-of-magnitude figures, and therefore less than 10% of the expected final quantity is provisionally allowed. The number is based on "composition of the waste material, character of the water mass, marine biota present, and the habits of the human population concerned." In addition to these new discharges, there are the routine discharges to the sea from the U. K. Atomic Energy Authority facilities at Windscale and Calder Hall, Chapelcross, Winfrith Heath, Dounreay, Springfields, and Capenhurst.[10]

The French will discharge the wastes to the North Sea from the processing center at La Hague for their civilian nuclear power complex.[11] Because of the strong currents during certain parts of the day, discharges will be limited to those hours to induce extra dilution. The center was expected to commence discharges in late spring 1966 (Ref. 12).

During the 1959 Monaco meeting,[13] the Japanese indicated their intention of discharging low-level wastes into the ocean. Political and social conditions within the country, however, have prevented any large-scale releases from Japanese installations. There are small-scale releases from Swedish,[14] Danish,[15] Indian,[16] Dutch,[17] and Australian[18] installations.

The number of installations that purposely discharge radioactive wastes directly into the ocean or estuaries or into river systems that eventually reach the ocean is obviously increasing. However, at the present time the releases from Windscale directly into the sea and from Hanford Operations into the Columbia River and eventually into the Pacific Ocean are the predominant releases to the oceans,[19] with about 800,000 curies (Ref. 20) and 5,250,000 curies (Ref. 21), respectively, during the last 13 years. The major portion of the radionuclides released from the Hanford Operations into the Columbia River have short half-lives. It is of interest to note that their total releases of radionuclides from Windscale and Hanford to the oceans are less than the ^{90}Sr alone deposited in the oceans from fallout.

The increase in disposal in the sea in solid form is more difficult to evaluate since the curie totals are far less determinate. This is in part due to the difficulty of measuring the average concentration of radionuclides in solid wastes, and in part due to the reluctance of some of the disposers to identify themselves or the magnitude of their disposals. However, based on U. S. experience with solid-waste discharges,[22] investigation of the behavior of typical containers as they descend to the ocean bottom,[23] and surveillance of the Pacific Coast deposition sites,[24] it is possible to state that, although relatively large quantities of solid wastes[22] (61,000 curies) were discharged to the ocean from 1946 to 1963 and in some cases the integrity of the containers was not maintained, samples of mud and water taken at the burial location on the ocean bottom have shown no detectable radioactivity.[25] Investigations at disposal sites in the Atlantic Ocean have given the same results.[26] Although the United States no longer disposes of solid wastes to the oceans because of the higher cost than land burial, other nations still dispose of some of their solid wastes at sea.

What Is the External Dose to Humans from Radionuclides in the Ocean?

The answers to questions regarding exposure are interrelated and are also philosophical and political in nature. Most of the Western countries, and the United States and Great Britain in particular, believe that the actual damage incurred by man and his environment is the limiting criterion, whereas the Soviet Union, in a more conservative interpretation of the same fundamental ICRP doctrine, requires that the releases to the environment meet drinking-water and breathing tolerances.[5] Consequently there have been profound disagreements as to permissibility of discharging wastes to the oceans. Typical of the Soviet position is the statement by Federov: "The Soviet Union always has been and will be a supporter of the strictest measures for the prevention of radioactive contamination of the ocean."[27] In line with Western "policy," based upon an assumed discharge, the maximum dose that would be received by individuals using the sea for swimming, boating, and fishing is computed; if this should prove to be above permissible limits, the permissible discharge limit would be reduced.

Typical of the studies upon which Western policy is based were those at Windscale, where it was shown that ingestion of seaweed was the limiting route.[28] In other cases, external dose has been the limiting route for establishing the amount of nuclides that could be discharged.[29] At Berkeley, England, the external dose to fishermen (0.5 rad/year) from concentrations of radionuclides on silt was the most restrictive limitation on discharges, whereas at Hinkley Point it was the external radiation (0.5 rad/year) from sediment and fishing gear that was the limiting factor. In the United States the external doses to individuals near and in the Columbia River prior to the time the water reaches the ocean is greater than doses received in and near the ocean, and consequently the dosages in and near the Columbia River are greater and would be limiting should the release rate ever get sufficiently high. Estimates indicate that swimmers in the vicinity of Richland (total immersion) for 240 hr received 20 mr during 1965, that water skiers and boaters at the same point received less than 10 mr, and that fishermen spending 500 hr on the shore received 15 mr. Therefore, if the same person spent the unlikely total of 1000 hr in and about the river in 1965, he would have received 45 mr (Ref. 30). Consequently, in answer to question three, it may be said that the dose received by humans from external exposures in the ocean due to the discharge of radioactive wastes may be the limiting factor in discharges permitted, although this is not the case at either Hanford or Windscale.

What Is the Dose to Humans from Seafood Products?

The dose to human beings from ingestion of contaminated seafoods might be obtained directly from whole-body measurements, but this presents difficulties in getting the members of the population affected to be counted. However, some of the staff members at Hanford and some of the potentially most affected members of the population near Hanford have been whole-body counted. Body burdens of ^{65}Zn have ranged up to 130 nanocuries for a controlled diet of fish eaten by one individual who would be classified as an occupational worker. About 95% of the body burdens of ^{65}Zn were less than 10 nanocuries. The maximum permissible body burden for the general population is 2000 nanocuries. Exposures received by the "maximum individual" (i.e., one who would be expected to have the highest exposure due to maximizing all potentially contaminated intakes) in 1965 have been calculated for people living near the Hanford plant. The computed bone dose was equivalent to 1.4% of the 168-hr occupational intake and was primarily due to ^{32}P in fish. Total-body dose was about 35 mrem and was due primarily to ^{32}P and ^{65}Zn in fish and in water and to external exposure to ^{65}Zn in water and on the shoreline. The gastrointestinal-tract dose was 80 mrem, due again primarily to ^{32}P and ^{65}Zn in fish and water.[31] The whole-body counts for the ^{65}Zn body burdens were about 3% of the computed doses,[32] which is understandable since the computed doses were based on maximum figures in each mode of exposure. More often the dose is obtained by estimating the food intake and measuring the concentration of radionuclides in foodstuffs. At Windscale the intake by those who ate 75 g per day of seaweed in laver bread in 1959 was as high as 74% of the ICRP permissible concentrations for the general population (i.e., 7.4% of the occupational intake).[33] This has decreased to 4, 1.8, and 2.1% of the occupational intake in 1960, 1961, and 1962, respectively. It is possible to estimate or measure concentration factors by the edible organisms and thereby determine permissible discharges. There have been a number of examples of this rationale both by the U. S. National Academy of Sciences committees[34-36] and the International Atomic Energy Agency's panel on Disposal into the Sea[37] and by the British[38] for particular situations. The procedures are widely applicable.

The Specific Activity rationale has also been suggested. In this approach, if the specific activity (the ratio of the quantity of radioisotope to that of total isotope of a chemical element) "of the elements of the sea in the region of the growth, development, and habitation of marine food organisms can be maintained below the allowable specific activities of these elements in man and his seafood, the allowable radiation for any individual cannot be exceeded as a result of the consumption of marine products" (Ref. 35, p. 22). This approach, of course, is only applicable to the total intake by an individual and is not applicable to the development of maximum permissible concentration values for water or air. However, it assumes that the stable and the radioactive isotopes are equally available for incorporation into the body, which may not be true. It also assumes that equilibrium conditions are attained if the specific activity in the body is to equal the specific activity in the water.

An interesting observation on the reason for the low internal doses to humans from discharges to the ocean has been offered by Isaacs.[39] He points out that those elements normally concentrated the most by man (such as iodine, calcium, and strontium) are very abundant in a marine environment and that the radioisotopes of those elements are consequently greatly diluted (i.e., the specific activity is low). Those elements rare in the marine environment and most concentrated by marine organisms, such as cobalt, iron, zinc, vanadium, and nickel, have short biologic half-lives in man, and consequently their radiological effects are reduced.

The estimates of doses received by the human population from the purposeful introduction of radioactive wastes into the environment have been exceedingly small. The report[40] of the United Nations Scientific Committee on the Effects of Atomic Radiation states: "Doses to the world population from either accidental or controlled releases of wastes have been negligible so far in comparison with those due to nuclear explosions, particularly those carried out above ground."

What Is the Effect of the Introduced Nuclides on the Ocean Flora and Fauna?

The question about which there has been perhaps the most vigorous debate concerns the effects of the release on the biota. The most concentrated sources are again those at Windscale and those at the juncture of the Columbia River with the Pacific Ocean. The concentrations in the water at the end of the pipeline at Windscale are given in Table 2 for the most significant isotopes and for the approximate concentrations and concentration factors of the seaweed and invertebrates.[41] Data for the vertebrates are also available[42] and have been added to Table 2.

Table 2 CONCENTRATION FACTORS OF VARIOUS ISOTOPES OFF WINDSCALE DURING 1959–1960

	Isotope				
	^{106}Ru	^{144}Ce	^{137}Cs	^{95}Zr–^{95}Nb	^{90}Sr
Concentration in seawater, pc/ml	0.15	0.03	0.02	0.08	0.012
Concentration in seaweeds,* pc/gww (especially Phacophyceae)	250	20	1.4	70	0.5
Accumulation factors in seaweed	2×10^3	7×10^2	70	10^3	40
Concentration in invertebrates, pc/gww	300	55	3.0	110	0.3
Accumulation factors in invertebrates	2×10^3	2×10^3	1.5×10^2	1.5×10^2	25
Concentration in vertebrates (fish), pc/gww	2.0	0.5			0.05
Accumulation factors in vertebrates (fish)	15	25			4

*gww = grams wet weight.

Concentrations of nuclides discharged from the Columbia River into the Pacific Ocean are also available[21,43] and are listed in Table 3. An excellent compilation of accumulation factors is that of Mauchline and Templeton.[44]

Although there has been comparatively little work at low levels of irradiation, American and British investigators studying the effects of low-level irradiation of fish populations have pointed out that[45]:

1. Most investigations to date have involved high doses of acute radiation. "Much less attention has, however, been paid to the radiation doses received by aquatic biota under chronic conditions in the environment, and very little has been published on the radiation regime in contaminated waters."
2. At low levels of irradiation, considerable difference in effects exists among similar species and among the various developmental states of the same species.
3. For acute radiation the less specialized forms are more resistant to radiation dosage than the more specialized forms.
4. Levels for somatic and genetic damage differ markedly.
5. Soviet scientists[46] claim that damage is detectable in marine fish (anchovy eggs) at concentrations of ^{90}Sr as low as 10^{-10} curie/liter, which is the level of ^{40}K in seawater.

The possibility of such low doses leading to significant changes is explained by ^{90}Y concentration of 100 in roe and a further concentration in the shell, which leads to accumulation factors in the shell of 10^4 and therefore to significant doses of about 0.1 of the natural background dose to the eggs.

British[47] and American[48] investigators, however, have results that are quite different. The British have shown that, for brown trout eggs in ^{90}Sr concentrations of 10^{-10} to 10^{-5} curie/liter, only at 10^{-6} curie/liter did significant differences in length, but not in percent hatch, begin to manifest themselves. The total dose to the eggs was equal to 4 rads in 58 days at 10^{-7} curie/liter. These investigators have suggested that, since this value differs markedly from the Russian value, perhaps different species, experimental conditions, and the short period of experimentation might be responsible in part for the difference.

Table 3 CONCENTRATION FACTORS FOR VARIOUS ISOTOPES IN THE OCEAN OFF THE COLUMBIA RIVER

	Isotope					
	^{65}Zn	^{51}Cr	^{103}Ru–^{106}Ru	^{95}Zr–^{95}Nb	^{141}Ce–^{144}Ce	^{54}Mn
Concentration in seawater,* pc/ml	0.350	1.3	0.003	0.016	0.027	†
Concentration in plankton,‡ pc/gdw*,§	300	1200	24	29	51	7.7
Accumulation factor in plankton	860	920	8000	1800	1900	
Concentration in algae,‡ pc/gdw	880	190	78	26	64	3.7
Accumulation factor in algae	2500	145	26,000	1600	2400	
Concentration in invertebrates,‡ pc/gdw	1600	950	50	16	160	5.5
Accumulation factor in invertebrates	4600	730	16,700	1000	6000	
Concentration in vertebrates,‡ pc/gdw	69	4.9	1.5	0.55	0	0.35
Accumulation factor in vertebrates	200	3.8	500	35	0	

*January 1961 to June 1962; maximum filtered surface samples.
†Not detectable.
‡April 1959, April 1960.
§gdw = grams dry weight.

The American experience can be summarized by the following quotation: "All of these experiments considered together show that the administration of 0.5 R/day from time of fertilization up to the feeding stage produced no detected damage to the stock sufficient to reduce the reproductive capacity over a period of slightly more than one generation."[48]

Therefore there is no conclusive answer to the fifth question. The British and American data show that, at water concentrations 10^{+3} greater than those experienced in actual liquid-disposal operations, there is no effect, whereas the Russian data indicate that effects are present. Since the experimental species and the form of chemicals are not identical and since differences in behavior are well known for both these variables,[49] the results may not be too surprising.

Disposal from Reprocessing Plants

The amounts of radionuclides to be discharged from plants reprocessing fuels from the civilian nuclear power plants are not expected for some time to exceed the amounts of those presently being discharged from plants operating for plutonium production, and improved processes will tend to reduce the total amount of nuclides released. At Windscale, although the tons of uranium processed have increased substantially, the total load of nuclides released has not increased.[50] An increase in the neutron-induced activation products is predicted, however. If the power plants used one-through cooling streams, this would cause increasing difficulty since some induced activities may be of greater metabolic significance than fission products.[51] However, since all civilian nuclear power plants use recirculating coolants, this, again, will not pose a major hazard.

There is no serious consideration of the disposal of high-level activity wastes to the oceans, and discharges of low-level wastes are proceeding only after exceedingly conservative investigations. Examples of such a conservative approach are given in a series of papers about the Solway Firth.[52-60]

Conclusion

Purposeful disposal of radioactive wastes to the sea is increasing, but, at present, levels of disposal do not present a significant hazard to man. As with all point sources of release, the hazard to man generally decreases with distance from the point of release due to various concentration reduction factors in the water and, consequently, to lower levels of concentration in the biota. There may be some food chains that are only initiated further downstream and hence can present a greater specific hazard at that point (for example, the reconcentration of ^{65}Zn by oysters). However, whether or not harmful effects to the environment have occurred has not yet been determined due to diametrically opposed results of the investigations carried out to date on genetic damage to biota from the wastes released.

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SAFE LEVELS OF RADIOACTIVITY IN AQUATIC ENVIRONMENTS

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As nuclear energy supplies ever-expanding proportions of man's power requirements, the dose of background radiation to man from his environment will increase. The continuous disposal of radioactive wastes into aquatic environments should be evaluated on the basis of long-term population effects from chronic exposure to low-level radiation. In this article, we discuss the implications of radioactive waste disposal into aquatic environments, and consider those aspects of radiation physiology, radioecology and health physics used in developing standards for the adequate protection of aquatic ecosystems and man from excessive doses of radiation.

INTRODUCTION. — The rapidly expanding use of nuclear fission for power production and desalination has resulted in widespread introduction of radioactive materials into aquatic environments. Once radioactivity enters the environment, only physical decay can eliminate it. We are therefore faced with the problem of disposing of radioactive wastes in a manner that will not endanger the future use of our environment. In this paper we examine the techniques applied to the protection of aquatic environments from undue radioactive contamination which might adversely affect the availability of any food resource or subject man to unhealthful radiation doses.

Two general approaches have dominated the disposal of radioactive wastes. Highly radioactive materials usually are concentrated to a minimum volume, then packaged in a semi-permanent shielded container and stored in a place far removed from human activity. This is the principle behind storage of radioactive wastes in underground tanks, in thin cement grouting layers in deep rock strata, and in concrete packages at the bottom of the oceans (International Atomic Energy Agency 1965, National Committee on Radiation Protection 1954a, Struxness In Press). In this paper we focus on the second concept of waste disposal, in which low-level radioactive wastes are diluted and dispersed directly into the environment.

The primary source of environmental contamination to date has been fallout from atomic test explosions, but the relative contribution from this activity is expected to continue to diminish in the future. Instead, wastes will arise from increased use of radioisotopes in clinical and experimental research applications and, principally, from the use of nuclear reactors in power plants and ships, including submarines. During typical reactor operations, fission products are not released, but occasionally a fuel element may rupture and leak into the cooling

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water. Additional radionuclides, however, are induced in the coolant water as it passes through the regions of high neutron-flux within the reactor, and this induced radioactivity is expelled intermittently from the reactor. This problem of disposal is especially urgent on a nuclear submarine where little space is reserved for storage of wastes. Another potential source of radioactivity in the environment is from the use of nuclear explosions for excavation, as in canal or harbor construction. Underlying any additions of artificial radionuclides to the environment must be the premise that life, including man, can safely tolerate a limited but sustained increase in radiation from the environment.

This premise undergoes continuous scrutiny from certain scientific bodies which were established for the express purpose of evaluating effects of radiation on biological systems, and especially on human beings. These scientific bodies include the International Commission on Radiological Protection (ICRP), sponsored under the International Society of Radiology; the U. S. National Committee on Radiation Protection and Measurements (NCRP); the Committees on the Biological Effects of Atomic Radiation, under auspices of the National Academy of Sciences—National Research Council; the United Nations' Scientific Committee on the Effects of Atomic Radiation; and the Federal (U.S.) Radiation Council (FRC), which was designed to provide governmental policy on human radiation exposure. Other nations also have governmental agencies with functions similar to those of the FRC. As suggested by this listing of national and international scientific bodies, the protection of human beings from overexposure to atomic radiation is of vital concern. The problems in determining what amount of radiation constitutes overexposure are manifold and imposing. The earlier committees, especially the ICRP and NCRP, were initially concerned with the protection of radiation workers, and have therefore recommended limits for occupational exposure to radiation, both from internal (NCRP 1959, ICRP 1960) and external sources. These recommendations were designed to protect an individual during his normal life-span from adverse effects of radiation.

With the advent of environmental contamination by wastes from the worldwide use of nuclear fission for power, our primary concern should perhaps shift from the radiological protection of individuals to protecting the genetic stability of the entire world population. Whereas an adult individual can tolerate safely 5 rems (r) per year (NCRP 1954b, 1959; ICRP 1960), it has been estimated that a dose of only 30-80 r, accumulated by the gonads, might double present mutation rates with uncertain consequences to the population (NAS-NRC 1956). For this reason, scientific committees on radiological protection have more recently re-evaluated in terms of genetic effects the premise that a sustained increase in environmental radiation is safe.

Let us now examine that premise and then consider the additional information required for establishing those « limits of safety » for radioactivity in our surroundings, especially as applied to aquatic environments.

HUMAN RADIATION TOLERANCE. — Although life began, and species evolved, in the presence of radiation—radiation from cosmic sources and from naturally occurring radioisotopes such as radium, carbon 14, and potassium 40—geneticists are almost unanimous in the view that any ionizing radiation is genetically undesirable. For example, Grosch (1965) states « Some natural radiation is unnecessary and may be potentially harmful. Included in this category are cosmic rays, body burdens of C^{14} and K^{40}, and the gamma radiation from earth, rock and the structural materials of our buildings ». The natural radioactivity from these sources obviously cannot easily be avoided and must be accepted as a normal hazard of living. The level of background radiation depends on altitude (elevation), latitude, and type of rock strata, and the dose may vary from 53 mr/year (to an individual on the open ocean at the equator) to 560 mr/year (at 55° N latitude, 20,000-foot elevation, on granitic strata) (Libby 1955, Kinsman 1958). A reasonable average dose is 140-150 mr/year. Since people have lived under similar circumstances of natural selection for several generations in areas differing by 150 mr, or more, per year in dose of natural radiation it is probable that an increase of 150 mr/year would constitute no threat to the genetic stability of human populations. We cannot say that an increased dose of 150 mr/year is the limit of safety, or even that it approaches that limit, but we can state with some confidence that an additional 150 mr/year would not be genetically critical. Such an increase would result in an additional 4.5 r accumulated dose to the gonads at age 30, the average parental age at the birth of any child in the U. S.; and 6.75 r at age 45, when reproduction more or less ceases. It is significant that the limits recommended elsewhere generally approximate this dose (Table 1).

TABLE 1

Recommended Limitations on Radiation Dose to General Population

Source of recommendation	Accumulated whole body dose at age 30 (rems)
ICRP (1959, 1960, 1966)	5[a]
NCRP (1954b, 1959)	14[b]
NAS-NRC (1956, 1960)	10[c]
FRC (1960)	5[a]

[a] Exclusive of background and medical exposure.
[b] From all sources, including background and medical dosages, averaged for 10^6 population.
[c] Exclusive of background, but including medical exposure.

We have considered in the foregoing discussion the levels of radiation which can be safely tolerated genetically by the general population. If only limited portions of a population are exposed, then greater doses can be withstood with no significant genetic effects to the whole population. Individual adults can tolerate much higher doses because the radiation-sensitive genetic material is no longer of prime consideration. The committees on radiation safety instead consider certain somatic effects, such as leukemia, or shortening of life-span, which might appear at some time following a latent period after exposure to radiation. The recommendations made by ICRP, NCRP, and FRC for maximum exposure of individuals working with radioactivity are identical: that occupational exposure will not exceed a whole body (or gonadal) dose of 3 rems during any period of 13 weeks, and that the accumulated dose at age N years shall not exceed 5 (N-18) rems, or in other words, 5 rems per year after age 18 (when occupational exposure might start). This limit of 5 rem/year is based upon exposure of whole body. Less sensitive portions of the body, especially if not significantly involved in blood formation, can tolerate still higher doses. For example, the dose permitted (NCRP 1959) for the hands, forearms, feet, and ankles is 75 rems/year. The ICRP (1960) also specified two alternate standards: a maximum dose of 1.5 rem/year for non-radiation workers who work near or occasionally visit controlled areas; and a maximum dose of 0.5 rems/year for the general public living in the neighborhood of a controlled area. These standards for different segments of the population are summarized in Table 2.

TABLE 2

Recommended Maximum Permissible Annual Doses of Radiation for People in Different Exposure Categories (ICRP 1959, 1960, 1966)

Group exposed	Maximum permissible dose per year (rems)[a]	Relative dose
General population	0.17	1
Communities in vicinity of controlled areas	0.5	3
Occasional visitors to controlled areas	1.5	9
Radiation workers	5.0	30

[a] All specified limits are for total whole body dose from both internal and external sources, exclusive of background and medical exposure.

STANDARDS APPLICABLE FOR GENERAL ENVIRONMENTAL CONTAMINATION. — The question now arises as to which set of standards should be applied to the control of waste disposal, and we might answer quickly that all should be used—each for its intended application.

This approach is certainly valid, now, while nuclear reactors are still relatively scarce, and significant doses may be encountered only in very limited areas in the immediate vicinity of nuclear operations. When a power company plans to build a nuclear power station near the Atlantic Coast in northeastern United States, it need not be concerned about the effects of its radioactive effluent on the genetic stability of the world population, or even of the population of northeastern United States. There would be no such effects at this time. It is likely, however, that the power company would already need to consider whether its anticipated effluent wastes will significantly affect food and water resources of communities living near the proposed reactor site. It requires little foresight, therefore, to become concerned about eventual levels of environmental radioactivity from the mushrooming expansion of peaceful uses of atomic energy.

If nuclear energy is used to supplement the rapidly decreasing supply of fossil fuel, and also to convert sea water to satisfy our increasing demands for fresh water, we can anticipate a gradual increase in environmental radioactivity during the next several centuries. This increase will become more pronounced as presently underdeveloped nations become more industrialized. As the use of nuclear power becomes more and more widespread, the concern must eventually be expressed for the general population. Since industrial pollution is more easily controlled during its initial phases, instead of after some unacceptable level has been established, it seems reasonable to think now in terms of future safe limits for the general population, even though exceeding those limits may present no immediate cause for concern.

CHARACTERISTICS OF AQUATIC ENVIRONMENTS THAT INFLUENCE WASTE DISPOSAL. — The role of water in the development of human culture and civilization has been almost as significant as its role in the evolution of life itself. Water not only provides the essential fluid medium in which all biochemical phenomena characteristic of life occur, but is an environmental resource so important that the volume of water in use by commercial and personal interests in the United States already approximates the total amount of water available from rainfall in the country (Anonymous 1966).

Human Use of Natural Waters. — Water is important to man primarily in two ways: a) Biological needs—we consume water as drinking water and also as an essential part of the food we eat—and b) industrial needs—here water serves mainly as coolant and diluent for carrying away excess heat and chemical wastes. As we shall see, biological and industrial needs for water conflict in many ways. The biological need for water includes farming—both agriculture and aquiculture (or mariculture). The use of water in aquiculture is obvious; in agriculture, natural rainfall is supplemented by irrigation from reservoirs or from desalinization plants, and crop production may be increased also by the use of commercial fertilizers made from seaweeds or fish meals from a distant sea.

The biological resources from aquatic ecosystems, especially from our estuaries and oceans, may be used both indirectly (fertilizers and animal feed) and directly (fish, shellfish, algae) for human food. Another biological « use » of the aquatic ecosystem is as a medium for bacterial conversion of industrial and municipal wastes either to harmless materials or to useful resources. Other uses of water include transportation (people and freight) and recreation (swimming, boating, sport fishing). Industrial contamination must be restricted so that aquatic ecosystems can maintain the capacity to support these essential functions.

Radioisotopes, along with heat and certain chemical toxins, are among the contaminants not reconverted biologically. Once diluted in the environment, radioactivity is attenuated only by physical decay. It is, however, continually cycled within the ecosystem—through plants, animals, sediments, and water. Our continued use of the aquatic environment, which no doubt will be more intensive in the future, will therefore provide many avenues for the return of discarded radioactivity to man.

Modes of Exposure to Artificial Radioactivity. — Exposure of humans to radiation from disposed waste in the aquatic environment is from external and internal sources. External exposure arises direct from contact with contaminated water, as in wading or swimming, handling fishing gear, relaxing on sandy beaches sprayed or occasionally covered with water, ... The doses received from external exposure will probably be small compared with internal doses obtained from eating radioactive seafood and drinking radioactive water. Additional internal exposure will arise from food made radioactive from fertilizers or irrigation water. How can we restrict and regulate disposal of radioactive wastes to protect humans from excessive radiation doses from the above sources? How do we transform our standards for acceptable dose level into specific limitations on radioactive contaminants released in any particular situation? The basic technique has been to restrict the concentrations of total radioactivity and of individual known radioisotopes in the environment, and more especially, in drinking water (ICRP 1960, NCRP 1959). For any given radioisotope, the concentration in drinking water which, if consumed continuously at a rate of 2.2 liters of water per day, would result in the maximum permissible dose, is called the maximum permissible concentration (MPC).

The Concept of Maximum Permissible Concentrations. — The information and assumptions needed for the calculation of a maximum permissible concentration might be illustrated best by the step-by-step development of one such MPC for a specific radioisotope. For this purpose, we have selected zinc 65, a neutron-induced radioisotope which is present in worldwide fallout and reactor effluents, and which is metabolically active in most organisms. The information and terms used for the computation of an MPC for zinc 65 in human drinking water are presented in Table 3.

Maximum permissible concentrations in drinking water for occupational exposure have been calculated (ICRP 1960) mainly by assuming that radioactive material is taken into the critical organ at the rate of P μc/day and that the biological elimination from the critical organ follows a simple exponential law. Thus, the radioactive burden of the critical organ varies with time as follows:

$$\frac{d\ (qf_2)}{dt} = P - \lambda\ (qf_2)\ \mu\text{Ci-day} \qquad (1)$$

TABLE 3

Information used for Calculation of MPC for Zinc 65 in Human Drinking Water

Term		Definition	Value for zinc 65
E	[a]	Energy (Mev) absorbed by critical organ per disintegration	—
ε	[b]	Effective energy = $\Sigma EF\ (RBE)n$	0.32 Mev/disintegration
F	[a]	Ratio of disintegrations of daughter to disintegrations of parent	—
f_2		Fraction of q located in critical organ	1.0
f_w		Fraction of ingested radionuclide that reaches critical organ	0.1
λ		Effective decay constant = 0.693-T	0.00357
m		Mass of the critical organ (whole body)	70,000 g.
$(MPC)_w$		Maximum permissible concentration of radionuclide in drinking water	—
n	[b]	Relative damage factor for radionuclides in bone	—
P	[b]	Rate of uptake by critical body organ (μCi/day) = 2200 $(MPC)_w$ (f_w)	—
q	[c]	Maximum permissible body burden = 2.8×10^{-3} $mR/f_2\ \varepsilon$	60 μCi
R		Maximum permissible dose = 5/52 rems/week	0.098 rems-week
RBE		Relative biological effectiveness (1 for x, γ, β^-, β^+, e^- radiation)	1

T	Effective half-life $= T_r T_b / T_r + T_b$	194 days
T_b	Biological half-life	933 days
T_r	Physical radioactive half-life	245 days
t	Period of exposure = 50 years for occupational exposure	18,250 days

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[a] The effective energy term (ΣEF (RBE) n) assumes different forms for different isotopes, because of differences in decay schemes and in metabolic behavior. For different kinds of radiation, i.e., $\gamma, \beta^-, \beta^+, \alpha$, etc., E is computed differently (ICRP 1960). For γ radiation, E involves the maximum energy of the γ radiation (Mev), the fraction of the total disintegration giving rise to γ rays, the effective radius (cm) of the critical body organ, and a coefficient of absorption for the given photon energy. For zinc 65, the terms F and n are not considered because no radioactive daughter is present and zinc 65 does not principally endanger bone tissue.

[b] This calculation is based on the assumption that the average man consumes 2200 ml of water (as fluid plus foods) per day.

[c] $$2.8 \times 10^{-3} = \frac{100 \text{ erg/g rad}}{(3.7 \times 10^4 \text{ dps}/\mu\text{Ci})\ (1.6 \times 10^{-6} \text{ ergs/Mev})\ (6.05 \times 10^5 \text{ sec/week})}$$

If $qf_2 = 0$, then:

$$qf_2 = \frac{P\ (1 - e^{-\lambda t})}{\lambda}\ \mu\text{Ci} \tag{2}$$

Substitution of appropriate values of P and λ for zinc 65 (from Table 4) and rearrangement give:

$$(\text{MPC})_w = \frac{3.16 \times 10^{-4}\ qf_2}{Tf_w\ \ (1 - e^{-0.693\ t/T})}\ \mu\text{Ci/cm}^3 \tag{3}$$

Substituting values for q, f_2, T, f_w, and t (also from Table 4) gives:

$$(\text{MPC})_w = \frac{18.96 \times 10^{-3}}{19.4 - 19.4e^{-65.19}} \tag{4}$$

or

$$(\text{MPC})_w = \frac{18.96 \times 10^{-3}}{19.4} = 0.977 \times 10^{-3}$$

$$\cong 10^{-3}\ \mu\text{Ci/cm}^3$$

This value, $10^{-3}\ \mu\text{Ci/cm}^3$, is the concentration of zinc 65 in human drinking water that will deliver for continuous exposure a dose of 5 rems/year, the maximum dose allowed for occupational exposure (Table 2). If the maximum allowable dose is selected for some other segment of the population, the MPC must be decreased accordingly. The ICRP and NCRP have recommended MPC's for about 240 radionuclides, for occupational exposure from either air or water during a 40 hour week and during a 168 hour week. The recommended MPC for any single isotope must be diminished whenever exposure is from a mixture of radioisotopes, from air and water simultaneously, or from certain external sources of radiation. The MPC for any completely unknown mixture of radionuclides is set at $10^{-7}\ \mu\text{Ci/cm}^3$ for continuous occupational exposure.

The calculation of MPC's is entirely dependent upon biological information—data on elemental distributions and concentrations in various human organs, data on the average size of human organs and of humans themselves, data on the efficiency of accumulation of an ingested radioisotope by different organs, and data on the elimination of elements from the various organs. For many nuclides and organs, these data not only are lacking for humans, but are extremely scarce for animals. This required information has been derived from experimental results wherever possible; when facts are completely unavailable, estimates are made by comparison with chemically similar elements, or by assuming steady-state conditions for an element in a critical organ. Elemental composition and distribution for a « standard man » were first stipulated during the 1940's, but these values have since undergone many revisions and additions. The composition of the standard (or average) man was summarized by the ICRP (1960). In nearly all cases, the critical body organ is the organ that accumulates the greatest concentration of the radioisotope under consideration. The body burden (q in Table 3) is that amount of the radionuclide in the total body, which results in the maximum permissible dose to the critical organ. For many nuclides, the MPC's were computed on the bases of various critical organs. For some—e.g., zinc 65—the total body may be considered the critical organ. Because the rates and efficiencies of uptake will vary for soluble and insoluble forms of the isotope, MPC's are also presented for both physical states; often the critical organ is also different for the two forms.

It should be clear from the foregoing discussion that the protection of man from environmental radioactivity is, to say the least, a complicated problem. The discussion of MPC's, up to this point, has been limited mainly to radionuclides in drinking water. When we consider waste disposal in the aquatic environment, however, we must be concerned primarily with radionuclides in foods. Since certain elements are concentrated to very high degrees by aquatic organisms, we must reconsider MPC's in terms of human consumption of fishery products.

APPLICATION OF MPC'S TO GENERAL CONTAMINATION OF AQUATIC ENVIRONMENTS. — Evaluation of aquatic contamination by radioactivity is complicated by the diverse environmental and biological variables which affect the disposition of a radionuclide introduced into the environment. Since the greatest potential hazard to man is almost certainly from the consumption of seafood containing radioactivity, the control of waste disposal into the oceans must be such that safe concentrations in edible organisms are not exceeded. Two divergent approaches have been proposed for effecting this control: the first is merely an extension of the widely accepted MPC concept, briefly described above; and the second is based on the premise that man cannot exceed his allowable body burden of any radioisotope so long as the specific activity of that isotope in the environment is maintained below the allowable specific activity in man. We will describe both of these approaches and discuss the merits and practicality of each.

Conventional Derivation of Working Limits for Radioactivity in the Marine Environment. — Permissible concentrations of radionuclides in the marine environment are usually calculated directly from the previously recommended MPC's in drinking water for continuous occupational exposure. Since this derivation involves additional information for which supporting data may be unavailable, certain assumptions must be made. Although the limiting concentration of any radionuclide will be found in edible organisms, the approach generally followed has been to establish limits for radionuclides in sea water (NAS-NRC 1959a, 1959b; Atea 1961; Yamagata 1965; Freke 1967). A nuclear power company can readily relate such limits to the levels of radioactivity in its waste effluent. These limitations placed on environmental contamination depend very much on local conditions, and should not be misconstrued as widely applicable « standards ». Rather, they are only derived working limits (DWL) based on the already established standards for maximum permissible radiation dose.

The first step in computing a DWL for sea water is to relate the MPC for drinking water to a DWL for seafood, as follows:

$$(\mathrm{DWL})_{\mathrm{sf}} = \frac{(\mathrm{MPC})_{\mathrm{w}}\ 2200}{30\ \mathrm{I}}\ \mu\mathrm{Ci/g} \qquad (5)$$

where:

$(\mathrm{MPC})_{\mathrm{w}}$ = MPC in drinking water for continuous occupational exposure - (μCi/cm^3).
$(\mathrm{DWL})_{\mathrm{sf}}$ = Derived working limit for radioactivity in seafood (μCi/g).
I = Rate of ingestion of seafood - (g/day).
2200 = Rate of intake of water assumed for calculation of $(\mathrm{MPC})_{\mathrm{w}}$ - (cm^3/day).
30 = Factor for converting $(\mathrm{MPC})_{\mathrm{w}}$ for continuous occupational exposure to that for exposure of general population (Table 2).

Inherent in equation (5) is the assumption that the efficiency of accumulation and retention and also the final tissue distribution, i.e., f_w, T, and f_2 (Table 3), are the same whether the isotope is ingested in drinking water of food. Supporting data for this assumption are sorely lacking for humans. In a recent series of papers, however, researchers described experiments in which human subjects consumed whitefish (*Prosopium williamsoni*) and oysters (*Crassostrea* sp.) collected in the Columbia River downstream from the reactor effluent. Accumulation of zinc 65 from these sources did not follow exactly the pattern predicted by application of the ICRP « standard man » values of 10 percent fractional absorption (f_w) and 194 days effective half-life (T). An experiment with only one subject eating whitefish gave $f_w = 32$ percent and $T = 162$ days (Foster and Honstead 1967). This fractional absorption of zinc 65 from whitefish was later confirmed in a 7-subject experiment by an average value of $F_w = 35$ percent (Honstead and Brady 1967). Accumulation of zinc 65 from oysters (again only one subject) gave $f_w = 13.5$ percent and $T = 100$ days (Honstead and Hildebrandt 1967). Although the sources of these differences are unknown, it is clear that the ICRP assumptions on radioisotope accumulation and retention are not necessarily exact for accumulation from various foods. Zinc 65 is absorbed more readily from oysters and fish than the ICRP assumed for uptake from drinking water. If this discrepancy is a general phenomenon, then DWL values for foodstuffs calculated by equation (5) will need to be decreased accordingly.

One possible explanation for the differences in efficiency of assimilation is that transport of zinc across the mucosa is facilitated by the presence of protein in the gut. The circumstantial evidence for this hypothesis is presented in Table 4.

TABLE 4

Protein Content of Food and Uptake of Zinc 65 from Different Sources

Source	Efficiency of Assimilation f_w	Percentage Protein Content P_c
Drinking water	.10[a]	—
Oysters	.135[b]	6.0[c]
Fish	.35[d]	17.9[c]

[a] ICRP (1960).
[b] Honstead and Hildebrandt (1967).
[c] Diem (1962).
[d] Whitefish - Honstead and Brady (1967).

A more probable explanation, which is completely unsupported at present, is that both assimilation efficiency and retention of an element depend on the total amount of that element in the diet.

The $(DWL)_{sf}$ calculated by means of equation (5) refers to the radioactivity in the food when it is consumed, not when it was caught. Applying this $(DWL)_{sf}$ to organisms while still in the environment would result in a safety factor for humans because physical decay of the radioactivity occurs during the interim between capture and consumption of the seafood. This factor is of little consequence for long-lived nuclides such as cesium 137 and strontium 90, but could permit elimination by decay of short-lived isotopes such as iodine 131. The $(DWL)_{sf}$ obviously refers also to the average concentration of radioactivity in any species of seafood eaten. Since many species of fish migrate during their life-spans, the variation of radioactivity among individuals may be high. Individual fish containing high levels of radioactivity will be diluted (in the natural population, and during commercial processing and marketing) by fish which are from other geographical areas and contain less radioactivity. « Market dilution » can be accounted for by permitting organisms in the immediate area of waste disposal to contain more radioactivity than is allowable for the average seafood consumed. A factor of 10 for this dilution has been suggested (Dunster 1958).

The rate of ingestion of seafood—I in equation (5)—should approach the maximum amount eaten daily by any individual, but must obviously be an approximate value. A reasonable approach would be to estimate the maximum intake for one year, then pro-rate the intake on a daily basis. People in different geographical locations and in different socio-economic or ethnic situations consume vastly different amounts and kinds of seafood. Various estimates of intake appear in the literature (Aten 1961; Yamagata 1965; NAS-NRC 1959a, 1959b; Weaver 1967). Values generally range from 110 to 250 g seafood consumed per day, and are based on the partial or complete fulfillment of the average dietary protein requirement by seafood. Freke (1967) did not specify an average intake, but defined I in terms of an average daily protein requirement of 1 g protein per kg body weight;

$$I = \frac{100\ (70)}{P_c} \qquad (6)$$

where:

P_c = Percent protein content of seafood in question.
70 = Body weight in kg of standard man.

If we take the approach used for MPC's in drinking water, we assume that the entire protein consumption of the population is from seafoods and that the seafood constitutes the only source of radioactivity. The second assumption is already inherent in the calculation. To match the average protein consumption in the United States, a man would have to eat approximately 1.8 kg of fish per week (NAS-NRC 1959a), or $I = 260$ g/day. The $(DWL)_{sf}$ based on this value for I would be $\frac{2200}{260}$, or about 8.5 times the $(MPC)_w$ for the general population; would have to be reduced to allow for other internal sources of radioactivity, including those from drinking water and other foods.

From the viewpoint of public health protection, it would probably be most practical to establish maximum levels of radioactivity for various types of foodstuffs, including seafood. This approach, however, is not practical for the control of waste disposal. Effective limits for controlling the rate of discharge of radioactivity into marine environments necessarily must be based on maximum levels for seafood, but must be expressed in terms of DWL's for the radioactive effluent (Aten 1961) or as maximum permissible rates of release, in curies per day (Freke 1967).

Derived working limits for sea water are obtained directly from $(DWL)_{sf}$ by dividing the ratio of the elemental concentration in the seafood to that in the sea water (concentration factor).

$$(DWL)_{sw} = \frac{(DWL)_{sf}}{C_f} \qquad (7)$$

It is evident that the value of $(DWL)_{sw}$ for any particular radioisotope depends entirely upon which organism is considered in the calculation. Widely different values for C_f have been reported for the same element or isotope among different groups of edible marine organisms. Since metabolic uptake and physical adsorption are both affected by physical conditions such as temperature, pH, and salinity, concentration factors for a given isotope in any single species must also be subject to wide variation. Concentration factors for different elements in aquatic organisms have only recently been compiled from the literature by Polikarpov (1966). Varying patterns of consumption of any given seafood species also affect $(DWL)_{sf}$, so that the $(DWL)_{sw}$ is a particularly vulnerable criterion. Freke (1967), in his derivation of $(DWL)_{sw}$, selected a single reasonable (or acceptable) value of C_f from the literature for each of a long series of radionuclides in four different groups of seafood organisms: fish, crustacea, molluscs, and seaweed. A similar, though less restrictive, approach presented by NAS-NRC (1959a) discriminated only between vertebrates and invertebrates. The group of organisms exhibiting the greatest C_f is considered limiting, and the $(DWL)_{sw}$ was computed on that basis.

Let us now complete our example. Zinc 65 generally is concentrated by oysters (*Crassostrea virginica* Gmelin) about 100,000 times the sea water concentrations of the isotope. For our purposes, we will consider this the limiting factor for zinc 65 in sea water. Thus, we have, from equations (5) and (7):

$$(DWL)_{sw} = \frac{2200\ (MPC)_w}{30 \times I \times C_f}\ \mu Ci/cm^3 \qquad (8)$$

where:

$(MPC)_w = 10^{-3}\ \mu Ci/cm^3$
$I = 260$ g/day
$C_f = 10^5$

and:

$$(DWL)_{sw} = \frac{2200 \times 10^{-3}}{30 \times 260 \times 10^5} = 2.8 \times 10^{-9}\ \mu Ci/cm^3$$

If equation (6) is used to calculate I (using $P_c = 6.0$, from Table 4), then $I = 1170$ g/day and $(DWL)_{sw} = 1.26 \times 10^{-10}$ μCi/cm³. As is usually the case in estimating concentration factors, grams and milliliters are considered equivalent in equation (8). The foregoing estimation of $(DWL)_{sw}$ is fraught with uncertainty. As discussed previously, the factors I and C_f are subject to wide variability, and uptake of an isotope from seafood is not necessarily equatable to uptake from drinking water. Perhaps the greatest uncertainty, however, arises from the arbitrary selection of a single species (necessarily one for which information is available) as the basis of the entire calculation. No single species is consumed at a uniform rate by the entire population. The use of an « average » value of C_f for a large group of similar organisms, e.g., molluscs, is also unacceptable, because certain species that constitute a significant part of the diets in certain localities may exhibit much higher concentration factors. Many of these drawbacks are eliminated from consideration in the application of the specific activity approach.

Derivation by Specific Activities of DWL's for Marine Environment. — The use of specific activity for establishing permissible levels of environmental radioactivity was first recommended for radioactive waste disposal into U. S. Pacific coastal waters (NAS-NRC 1962). Specific activity of any radioisotope is defined as the ratio of the amount of the radioactive isotope to the total amount of the element present (µCi/g, or equivalent). The application of this approach is based mainly on two assumptions: 1) that a radioisotope introduced into the environment readily equilibrates with the stable isotope (s) of the same element such that biological concentrating mechanisms will be unable to discriminate between the radioactive and stable forms, and 2) that the quantity of each stable element in each body organ is « fixed » and does not fluctuate with the intake of that element. Thus the distribution of radionuclides will correspond to the distribution of stable elements in the environment. The maximum permissible specific activity (MPSA) for any radioisotope with a critical organ other than the gastrointestinal tract is readily available from data on the standard man (ICRP 1959):

$$(MPSA) = \frac{q}{m \times C} \qquad (9)$$

where:

(MPSA) = Maximum permissible specific activity (µCi/g).

q = Maximum permissible burden of radioisotope in critical organ (µCi).

m = Mass of the critical organ (g).

C = Concentration of stable element in critical organ (g/g).

The (MPSA) is then converted to $(DWL)_{sw}$ (or, if desired, $(DWL)_{sf}$) simply by multiplying by the concentration of stable element in sea water (or in the seafood):

$$(DWL)_{sw} = K \times (MPSA) \tag{10}$$

where K = grams of stable element per cm^3 sea water.
The $(DWL)_{sw}$ so derived is independent of concentration factors and of rate of consumption of seafoods. If the MPC is set for sea water instead of for marketed seafood, then physical decay of the radioisotope will introduce a safety factor. Radioactivity accumulated by primary producers and then passed up a food chain to man will undergo physical decay during its residence in each trophic level. This process will be partially offset by continuous bioaccumulation from the water surrounding the organism, but for most elements the biological turnover is slow enough for physical decay to reduce significantly the specific activity of a radioisotope before the organism is consumed by organisms in the next higher trophic level. The extent of attenuation obviously depends on the physical half-life of the radioisotope and the residence time of the isotope in each trophic level.

The specific activity approach, as calculated in equations (9) and (10), should be applicable for any situation where the gastrointestinal tract is not a critical organ. For those radioisotopes which are not assimilated efficiently, the primary concern must be for the gastro-intestinal tract, and the $(DWL)_{sw}$ must be derived from the allowable radioactivity estimated for seafood organisms, as by equations (5) and (7). The shortcomings of this technique were discussed previously. The MPSA for an isotope with the gastro-intestinal tract as a critical organ could be calculated from the $(DWL)_{sw}$ and the elemental concentration in sea water (equation (10)). The specific activity approach might also be invalid in individuals that had consumed food and water containing the MPSA of a radioisotope for a very long time. In such a case, the body burden of the isotope would approach the maximum permissible body burden (but never reach it because of physical decay of the isotope during its metabolism) such that consumption of a meal containing high radioactivity, but still no more than the MPSA, would result in more than the maximum allowable burden for either the gastro-intestinal tract or the total body. This potentiality is of little immediate consequence, because environmental radioactivity certainly does not approach the MPSA's except (possibly) in extremely localized areas.

Certain examples of bioaccumulation have led investigators to question the premise that radioisotopes behave in the natural environment just as does the stable isotope of the element. For example, Schelske et al. (1966) postulated that bay scallops (*Aequipecten irradians* Lamarck) accumulated manganese 54 from particulate fallout in sea water because the specific activities of scallop tissues were higher than the specific activity of the water.

The results of calculating $(DWL)_{SW}$ for several isotopes by the specific activity and the conventional approach are compared in Table 5 (Isaacs 1964).

TABLE 5

Comparison of $(DWL)_{SW}$ Values Derived by Conventional and Specific Activity Approaches[a]

(1) Isotope	(2) PSC[b] conventional approach (μCi/ml)	(3) MPCC[c] specific activity approach (μCi/g)	(4) (2)/(3)
Cobalt 60	5×10^{-9}	5.0×10^{-9}	1.0
Iron 59	3×10^{-9}	3.0×10^{-9}	1.0
Copper 64	6×10^{-9}	6.0×10^{-9}	1.0
Zinc 65	2×10^{-8}	1.2×10^{-8}	1.67
Cesium 137	4×10^{-6}	1.5×10^{-4}	0.0267
Strontium 90	5×10^{-8}	3.4×10^{-5}	0.00147
Iodine 131	2×10^{-9}	1.6×10^{-6}	0.00125
Phosphorus 32	1×10^{-9}	2.8×10^{-9}	0.357
Sulphur 35	1.2×10^{-5}	8.4×10^{-3}	0.00143
Calcium 45	4.5×10^{-6}	1.2×10^{-4}	0.0375

Modified from Isaacs (1964).

[b] Permissible sea water concentrations as calculated in NAS-NRC (1959 a) but revised according to NRCP (1959) values for $(MPC)_w$, and according to the more recent biological concentration factors and the appropriate reduction factors for dose to the general population as recommended by NAS-NRC (1962).

Maximum permissible sea water concentrations recommended by NAS-NRC (1962). All values except those for cobalt 60, iron 59, and copper 64 were calculated by equations (9) and (10), but were then increased by decay factors appropriate for the physical and biological half-lives of each isotope.

Table 5 shows that the specific activity approach usually gives less stringent standards for radioactive waste in sea water. Since the first three nuclides in Table 5—cobalt 60, iron 59, and copper 64—have the gastro-intestinal tract as the critical organ, the derivations necessarily are identical, i.e., by equations (5) and (7). For other isotopes the specific activity approach permits up to almost 1000 times as much environmental radioactivity in sea water. It should be emphasized that the MPCC values (Table 5, column 3) were intended to represent the actual *limits of safety* for radioactivity in sea water, whereas the conventional approach (Table 5, column 2) includes many poorly defined safety factors. The specific activity approach has the following drawbacks: 1) it is not valid when considering radiation dose to the gastro-intestinal tract; 2) as a human approaches his maximum permissible body burden of radioactivity, the *total* activity of the contents of his gastro-intestinal tract becomes significant, regardless of what the *specific* activity is; and 3) radionuclides introduced into the environment may be more (or less) readily available for bioaccumulation than the corresponding stable element, i.e., the entire basis for the approach may at times be invalid.

The specific activity approach has special merit for those radioisotopes which, because of long physical half-life or of continuous introduction into the environment, are chronic contaminants. Such radioisotopes will have had ample time to equilibrate with the stable isotopes already present in the environment, so that after the initial period of introduction, most of the radioisotope will be distributed in the same way as a stable carrier. Such is probably the case with cesium 137 and strontium 90 from fallout in the biosphere, although neither isotope has yet equilibrated in the deeper parts of the ocean (Broecker, Bonebakker, and Rocco 1966). In any acute contamination, however, the radioisotopes may be introduced in a physical or chemical form different from that of the stable isotopes in the environment, and bioaccumulation of the radioactivity might be independent of the distribution of the stable element. At present, nearly all radioactivity introduced into the environment is comparable to acute contamination, because significant concentrations of most radioisotopes are not yet widespread, but are localized in the immediate areas of contamination. As radioactive contamination becomes widespread, i.e., as portions of the environment approach their « maximum permissible burdens » of radioactivity, the specific activity approach will become increasingly applicable. In the meantime, isolated instances of « acute » radioactive contamination might be controlled more effectively on the basis of the nature of the contaminating effluent and of the immediate environmental circumstances than on the basis of the distribution of stable elements in the receiving environment. The conventional approach necessarily involves many conservative approximations but nevertheless is based on sound principles of bioaccumulation, and will adequately protect the population from excessive radiation.

The techniques we apply to the problem of radioactive contamination of our environment must undergo continuous revision as new information develops.

Limits on the quantities of water-borne radioactive materials that can be released to the environment are now based on the expectancy that the receiving water will be used as a source of drinking water or that people will consume large quantities of fish, shellfish, or other aquatic or marine foodstuffs produced in the vicinity of the plant discharge. The calculations that lead to the specification of release rates (or maximum concentrations of radionuclides in the effluent) are based on conservative estimates of the behavior of the radionuclides in the receiving water, the reconcentration of certain radionuclides by aquatic and marine food organisms, the rates of consumption of edible parts of the food organisms, and the accumulation and retention of the nuclides in man. Many of the estimates now used are tentative and are probably overly conservative because of a paucity of definitive data.

Additional radioecological research is underway in many laboratories through the world to improve the estimates that are now being used, to provide greater assurance of the safety of the limits as now calculated, and to acquire the knowledge needed to cope with unplanned radioactive contamination. Further research is especially needed on the following:
1) the fate of radioactive materials discharged into natural waters, 2) the reconcentration of radionuclides by important aquatic organisms, 3) the efficiency of transfer of radionuclides through food webs, 4) the flux of acute releases of radioactive wastes through aquatic communities, and 5) the effects of chronic exposure to low levels of radioactive materials on aquatic organisms and populations. Continued research in these areas will ensure that we are neither too permissive nor excessively restrictive in our regulation of radioactive waste disposal into aquatic environments.

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Ecological Considerations in Siting Nuclear Power Plants: The Long-Term Biotic Effects Problem*

By Stanley I. Auerbach

Abstract: *One of the current concerns over the increasing installation of nuclear power stations is the potential impact of radioactive waste releases on local ecosystems. In particular, the question has been raised whether waste releases at maximum permissible concentration (MPC) levels would cause ecological problems due to the radioactivity. Hypothetical annual submersion dose rates from water assumed to be maintained at the occupational MPC x 1/30 were calculated for organisms living continuously in these waters. These hypothetical doses are used as a basis for comparisons in a variety of ecological studies of low doses of ionizing radiation and are analyzed and evaluated in terms of detectability of biological effects at MPC levels. Present knowledge based on these and similar studies of the ecological effects of low-level chronic doses, such as could result from routine reactor releases under current standards, guidelines, and operational experience, indicates that any possible biological effects would be undetectable. Although the data in support of this contention are limited, they consistently point to this conclusion.*

The rapidly expanding interest in the utilization of nuclear energy as a power source has started to focus public attention on benefits and risks associated with the peaceful uses of the atom. The context of the current concern differs markedly from the last period of major public interest in atomic matters, which occurred during the period of weapons testing, with its associated worldwide radioactive fallout. The current phase happens to be concomitant with a more general concern about environmental quality and with the impact of technology on the environment. Thus today the nuclear reactor, in terms of its potential as an economical energy source, represents a very important, if not essential, element among the several alternative technologies available to provide needed electric energy.

It is becoming increasingly evident that nuclear power will be a necessity if we are to continue increasing our usage of electrical energy at the current rate. Our limited fossil-fuel reserves, and questions regarding the successful or widespread application of some competing technologies (solar, geothermal, tidal), make nuclear power a necessary element of our long-range energy planning.

Any judgment of the risks and benefits associated with a nuclear power station should also include, as part of the complex of facts and variables that enter into the formulation of such a judgment, the risks and benefits associated with fossil-fueled power stations. Each kind of power station has an environmental impact associated with it that is more or less unique. For nuclear power stations this impact is generally associated with radioactivity. However, there is evidence that fossil-fueled power stations also may release radioactivity from their stacks,[1,2] so differences between power stations in terms of their impact on the environment may, in part, be quantitative, as in the case of radioactivity, or distinctly qualitative, as in the case of SO_2. The radioecological impact of power stations must be evaluated in the light of these considerations.

HISTORICAL PERSPECTIVE

Public interest and concern over environmental radioactivity has resulted in a gradually increasing growth in the atomic energy environmental research program. During the earliest years environmental studies and related surveillance were primarily centered on the major government-owned nuclear facilities, such as the Hanford Works and the Oak Ridge National Laboratory, where radionuclides were being produced and released to the environment in accordance with the prevailing standards. The Hanford Works was of particular interest because radioactive waste resulting from irradiation of the cooling water used in the large production reactors was discharged routinely to the Columbia River, which has important fisheries. An ecological analysis and surveillance program was established and now has documentation extending over 25 years on the behavior of the quantities of radionuclides released to the Columbia River and their consequences.

By the mid-1950s the potential of nuclear energy with its associated problems of radioactive wastes and concern over weapons fallout resulted in an intensification and broadening of effort in radioecology. The

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movement of radionuclides through food chains and the effects of radiation on the environment were quickly perceived as being the two major facets of the radiation problem. Likewise the effects of chronic, low-level ionizing radiation were early recognized as one of the most difficult, if not intractable, challenges facing radiation ecologists, especially radiation biologists concerned with the effects of low-level ionizing radiation on man. In this article some of the evidence is examined that bears on the long-term, low-level effects of chronic ionizing radiation on organisms within the natural environment.

Proper evaluation of the facts and related information on the environmental impact of radioactivity requires some perspective on the known effects of ionizing radiation to judge these data in the context of the quantities of radiation likely to be encountered in the vicinity of a nuclear power station. The quantity of radionuclides that may be released to the environment is legally limited on the basis of the hazard to man. The maximum permissible doses (MPDs) of radiation to man and the maximum permissible concentrations (MPCs) of radionuclides derived from these doses are evaluated continuously by regulating agencies and certain national and international scientific bodies established for the express purpose of establishing standards of permissible radiation exposure for man. These scientific bodies include the U. S. National Council on Radiation Protection and Measurements (NCRP); the Committee on the Biological Effects of Atomic Radiation, under auspices of the National Academy of Sciences–National Research Council; the United Nations' Scientific Committee on the Effects of Atomic Radiation; and the Federal (U. S.) Radiation Council (FRC), which was established to provide protection policy and standards on exposures of radiation workers and members of the public.

Other nations also have governmental agencies with functions similar to the FRC and the NCRP. All these groups and agencies were established because of concern over ionizing radiation and the need to protect man from overexposure to radiation. The problems in determining what quantity of radiation constitutes overexposure are manifold and complex. Nevertheless, it is to the credit of these agencies and to the hundreds of scientists who have conducted the many kinds of radiobiological research which provided the necessary data that a body of acceptable standards has been developed. Although the standards themselves are complex in both interpretatation and application, they reflect an effort in research and standards development which is unique and outstanding.

We have no comparable standards that apply to food chains in the environment. Research in radioecology during the past 15 years or so has been directed toward ascertaining the effects of radiation on natural populations as a function of dose. As this research matures, a body of doctrine is expected to emerge to provide the basis for development of any further standards that are shown to be necessary. Meanwhile the present standards provide both guidelines and a set of baseline levels that are useful now in comparing the known effects of chronic low doses of radiation on organisms against the legally permissible levels of radionuclide releases.

My concern here is with the potential effects of ionizing radiation resulting from releases of radionuclides that are in accordance with current standards. The extant data on low-level effects should be evaluated in terms of the doses that are likely to be received by organisms in the environment as a result of releases at or below the MPC. The MPCs and MPDs established by the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection (NCRP) form the basis for the regulations set forth in 10 CFR 20 (*Code of Federal Regulations*, Title 10, Part 20),[3] pertaining to the discharge of radioactive wastes by nuclear establishments. The standards of radiation exposure and therefore the MPCs differ for the population groups exposed. ICRP Publication No. 9 has established two categories of individuals for which the Commission now gives recommendations: (1) adults exposed in the course of their work (radiation workers) and (2) members of the public. Doses to individuals in the population and critical segments of the population should not exceed 500 mRems/year; total dose to the population as a whole should not exceed an average of 170 mRems/year (not including background and medical sources). Under current practice the actual exposure of the public from nuclear power stations has been estimated to be at least two orders of magnitude less than the dose limits.[4] The 170 mRem/year limit refers to dose to gonads, total body, and red bone marrow. No official guidance is presently available on how this 170 mRems/year should be apportioned among exposures from nuclear power stations, Plowshare applications, and industrial materials that produce ionizing radiation. Although Table 2 of Appendix B in 10 CFR 20 lists occupational MPCs x 1/10, it is implied elsewhere [Regulation 20.106(e) of 10 CFR 20] that these $1/10 \times (\mathrm{MPC})_{\mathrm{occ}}$ values should be multiplied by an additional factor of 1/3. Thus continuous exposure at $1/3 \times 1/10 \times (\mathrm{MPC})_{\mathrm{occ}}$ would result in a maximum dose rate of 170 mRems/year to total body, gonads, and red bone marrow of standard man. It is important to bear in mind that the primary criteria for assessing exposures of the public are the radiation-protection standards of 5 Rems/30 years for a genetically significant dose and an average of 170 mRems/year total body dose to the population as a whole. The MPCs are only secondary standards derived from the somatic dose limit.

A certain amount of experience already has been gained in operating nuclear power stations below the limits specified in 10 CFR 20. Blomeke and Harrington recently reviewed the waste-management experience of six operational power reactors: Dresden 1, Big Rock Point, Humboldt Bay, Elk River, Indian Point 1, and Yankee.[5] For liquid wastes, all apparently measured at the point of release to the discharge coolant canal, the activity discharges per year as a percentage of the limit (limit based on a continuous discharge averaged over 12 consecutive months) of 10^{-6} μCi/cm^3 (1 pCi/cm^3) of unidentified isotopes of plant origin ranged from a low of 0.0002% to a high of 9.9%. The average annual release rates (before environmental dilution) of gaseous radioactive wastes ranged from 0.00013 to 28% of the specified AEC license limits.

Since all the MPCs are derived for internal exposure of man, an obvious question relating to exposure of other organisms arises. What is the dose to organisms of natural populations submerged in water maintained at the $(MPC)_w$ or some fraction of the $(MPC)_w$ for individual radionuclides? Would these dose rates be expected to result in detectable biological effects to aquatic organisms over a period of time? The following tabulation gives the results of calculating the yearly dose rates at the surface of an organism submerged continuously in water containing various radionuclides maintained at the $(MPC)_w$ for man:

Radionuclide	Dose rate, rad/year
^{60}Co	0.797
^{54}Mn	0.526
^{51}Cr	0.377
^{65}Zn	0.342
^{140}Ba	0.0871
^{89}Sr	0.0658
^{137}Cs ^{137m}Ba	0.0596
^{132}I	0.0391
^{144}Ce–^{144}Pr	0.0173
^{106}Ru–^{106}Rh	0.00625
^{90}Sr	0.000236

This is a totally hypothetical exposure condition used here to illustrate in general terms external dose levels to aquatic organisms under these exposure conditions. The purpose of this calculation is merely to serve as a basis for comparison with actual experimental-dose response data cited later in this article. In actual practice the limit used currently around nuclear power stations of 10^{-6} μCi/cm^3 (1 pCi/cm^3) is one to several orders of magnitude lower than the MPCs for most of the individual radionuclides listed above.

How do these annual dose rates (and doses) compare with our current factual knowledge of the effects of ionizing radiation? The remainder of this article is concerned with this question.

It is not my intention to review the developing literature on the effects of large doses of radiation delivered in an acute or chronic mode. The interested reader can refer to several symposia on radioecology for fact and details.[6-9] In the area of radiobiology, the literature on effects, dose response, and survivorship is vast. There are nevertheless some generalizations that can be derived from this body of facts. An acute dose of 100 rads is the general lower limit that can be expected to produce mortality in a number of organisms but not in all. Depending on the biological end point, acute doses greater than 100 rads will produce an effect that is proportional to dose. On the other hand, under conditions of chronic doses, generally speaking, the effect is much less marked than for an acute dose. Moreover the lower the dose rate and the less the total dose, the more difficult it is to detect an effect. That is to say, more sophisticated means of detection must be used and more sensitive biological end points must be utilized as the basis for detection. When experimental dose rates are lowered to 1 rad per day, the number of factors affecting the organism are sufficient to mask any effects that might be present. Such commonly used end points as survivorship, fecundity, growth, development, and susceptibility to infection have not as yet been shown to be unequivocally affected by such low dose rates.

FIELD STUDIES OF LOW-LEVEL CHRONIC IRRADIATION OF BIOTA

Much current concern over power reactors is related to potential chronic effects of radiation on biota at levels lower than MPC levels. Therefore the remainder of this article will be a review of some of the findings made by a number of the workers in this difficult and at times frustrating field. Very few studies have been made on natural populations exposed to chronic radiation slightly higher than background.

Larvae in White Oak Lake

The salivary chromosomes of the larvae of *Chironomus tentans* (a nonbiting midge), which inhabits the radioactively contaminated bottom sediments of White Oak Creek and White Oak Lake at Oak Ridge National Laboratory, were analyzed for 5 years for chromosomal aberrations.[10-12] Calculations and measurements of the absorbed dose for larvae living in the sediments were 230 to 240 rads/year, or approximately 1000 times background for the area. Over 130 generations had been exposed to this or greater dose rates during the previous 22 years. Table 1 summarizes the number of different chromosome aberrations observed in irradiated and nonirradiated populations; the data include the White Oak Creek (irradiated), Ten Mile Creek (nonirradiated), and other populations. Column one shows a total of 17 different aberrations observed in the irradiated population. Column 2 shows that only six different inversions were observed in the nonirradiated populations and that all six of these inversions were also found in the irradiated population. These inversions were found in each population more than once, and three occurred at relatively high frequency. Eleven aberrations—10 inversions and 1 deletion—were observed only once, except for one inversion, which was found five times in two collections from one site and was probably the result of one event.[10] The frequencies of these unique aberrations, found only in the irradiated population, were very low when compared with the frequencies of the endemic inversions. Blaylock concluded that the occurrence of new aberrations in the contaminated area was increased by the high background radiation and that these new aberrations were rapidly eliminated by selection or genetic drift. If all new mutations and chromosome aberrations are considered to be deleterious, these findings could be construed as harmful; on the other hand the populations in this irradiated area show no signs of detrimental effects using population numbers and reproductive capability as criteria.

Table 1 Chromosome Aberrations in Irradiated and Nonirradiated Natural Populations of *Chironomus tentans**

	Irradiated populations	Nonirradiated populations
Larvae analyzed	692	714
Number of different inversions† found in both populations	6	6
Number of different inversions† unique to one population	10	0
Number of deletions unique to one population	1	0

*From Ref. 11.

†An inversion is a rearrangement of the genetic material in a chromosome that occurs when a deleted chromosome segment is turned 180° and reinserted at the same position in the chromosome. These data include the White Oak (irradiated), Ten Mile Creek (nonirradiated), and other populations.

The presence of endemic inversions at high frequencies in both populations provided Blaylock an opportunity to test the effect of ionizing radiation on the chromosomal polymorphism of these populations. Geneticists believe that polymorphic populations are superior in fitness to monomorphic populations because they can adapt to slightly changing environmental conditions. Therefore a decrease in chromosomal polymorphism could indicate a decrease in fitness of the population. Blaylock found there was no difference between the irradiated and control populations with respect to their chromosomal polymorphism, as evidenced in the endemic inversions. Therefore he concluded that the chronic environmental radiation that was capable of producing a detectable increase of new chromosomal aberrations was not affecting the frequencies of the endemic inversions in the populations of White Oak Creek and White Oak Lake.

Mosquito Fish in White Oak Lake

This radioactive habitat was also the site for another series of investigations by Blaylock.[13] In this case the natural population investigated was the hardy, highly adaptable mosquito fish, *Gambusia affinis affinis*. Approximately 100 generations of fish have lived in this area since the first release of radioactive waste effluents. In this investigation another parameter of population fitness, fecundity—the number of offspring per female—was considered, since laboratory studies have shown that it can be influenced by ionizing radiation. These fish lived in a shallow portion of the lake where the sediments contained above-background quantities of ^{137}Cs, ^{106}Ru, ^{60}Co, ^{90}Sr, and ^{65}Zn. On the basis of measurements and calculations, these fish were exposed to approximately 11 rads/day from external gamma radiation and 1.75 rads/year from internal beta radiation.

Fecundity data were obtained by collecting female *Gambusia* from White Oak Lake and the control area, measuring them to the nearest millimeter, and dissecting them for embryo counts. In 98 fish from White Oak Lake, 4625 embryos were scored. The brood size ranged from 13 embryos in a 3.0-cm fish to 105 in a 4.0-cm fish. In 98 fish from the control pond, 3257 embryos were scored, and the brood size ranged from 11 embryos in a 3.3-cm fish to 63 embryos in a 4.4-cm fish. The frequency of dead embryos and abnormalities was significantly greater in the irradiated population than in the nonirradiated population.

The most striking finding of this study, however, was the fact that the irradiated populations had a highly significant greater fecundity than the control population. Blaylock's paper marshals evidence that supports the idea that irradiation can increase the fitness of organisms. These data support the hypothesis that radiation-induced mutations, most of which would be deleterious in the homozygous condition, produce sufficient cumulative effects in the heterozygous condition to more than counterbalance induced dominant deleterious mutations. Apparently, under certain conditions, genetic variability resulting from radiation-induced mutations can improve the fitness of populations. Natural selection operating on a population with increased genetic variability results in an increased rate of evolution of the population and adaptation to environmental factors.

Increased fecundity of females in the *Gambusia* population in White Oak Lake may be an adjustment to the chronic environmental radiation. An increased mortality of embryos that could be attributed to ionizing radiation was also found in this population. In this respect radiation would be analogous to an environmental factor that increases mortality. Another effect of radiation would be the increased genetic variability resulting from radiation-induced mutations. This would increase the rate of evolution and speed up the adjustment of the population to the increased mortality. However, this would not occur without some expense to the population. Many genetic combinations would be selected against and the individuals eliminated. In populations with a relatively short life cycle, such as some fish and insects, where overproduction of the young is the rule and selection is severe, the population level could be maintained in spite of the elimination of many individuals.

Chinook Salmon

At the University of Washington, Progessor Lauren Donaldson has had under way a long-term study of the effect of chronic low-level gamma radiation on the chinook salmon (*Oncorhynchus tshawytscha*).[14-16] In these experiments eggs and alevins were exposed to rates of 0.5, 1.0, 2.5, or 5.0 R/day. Exposure began immediately after fertilization until the yolk was absorbed and the young fish were completely formed, a period of 80 to 100 days, depending on water temperature. The fish from the exposed lots and a like number from the control group were fed for a period of approximately 90 days before being released to migrate to the sea. In the ocean these young fish had to compete in a natural environment that presents many hazards. Upon return from the sea, the adult fish and their progeny were subjected to detailed study for all possible effects.

Results of this series of long-term experiments, with large numbers of fish, ranging from 96,000 to 256,000 fingerlings released per experiment, have given no indication that these high exposure rates are injurious to the fish. Irradiations at these early life stages have not caused significant mortality or retardation of growth in either smolts or returning spawners, or in fecundity. In fact, Donaldson and his coworkers report that at the lowest exposure rate of 0.5 R/day—an exposure rate that is 105 times greater than average background (0.01 to 0.02 mR/hr)—the irradiated stock returned in greater numbers and produced a greater total of viable eggs than the controls.

LABORATORY INVESTIGATIONS OF LOW-LEVEL CHRONIC IRRADIATION OF BIOTA

Additional insight on the probable ecological effects resulting from radionuclide release may be obtained from laboratory investigations. The number of investigations is too large to cover in this article; moreover they are treated more fully by Templeton, Nakatani, and Held.[17] Some that are illustrative of many of the findings are summarized briefly here.

Cell Division in Phytoplankton

Phytoplankton are important because they are one of the main bases of the ecological food chains of the ocean. Phytoplankton are known to accumulate a large number of elements including their radioisotopes, and concentrations may be reached that are much higher than those in the surrounding media. Rice and his coworkers (personal communication) tested the effect of ^{137}Cs on the division rate of a marine plankton *Nitzschia closterium.* The rate of cell division controls the population size, and cell division rate is an easily followed parameter. In one experiment the populations were started in a medium containing 14.3 μCi ^{137}Cs/liter (1.43 x 10^4 pCi/cm^3). After 26 weeks at this concentration, the cultures were transferred to media containing 10 times the previous concentration of ^{137}Cs (1.43 x 10^5 pCi/cm^3) and were followed for 30 more weeks. Rice and his group found no evidence of injury to cells or to the population during this period of time.

Table 2 Calculated Exposure Rates* for ^{65}Zn, ^{51}Cr, and $^{90}Sr-^{90}Y$

Concentration		Calculated exposure rates, rads/day		
pCi/liter	pCi/cm^3	$^{90}Sr-^{90}Y$	^{65}Zn	^{51}Cr
10^{10}	10^7	430	40.0	3.0
10^9	10^6	43.0	4.0	0.3
10^8	10^5	4.3	0.4	0.03
10^7	10^4	0.43	0.04	0.003
10^6	10^3	0.04	0.004	

*From Ref. 18.

Effect of Radionuclides on Oyster Larvae

Effects of ^{65}Zn, ^{51}Cr, and $^{90}Sr-^{90}Y$ on the development of oyster larvae were examined in a series of laboratory experiments by Nelson.[18] Concentrations of radionuclides used and dose rates resulting therefrom are shown in Table 2. In addition, stable zinc and stable chromium were also tested in conjunction with the nuclides for the effect of carrier on the organisms. The biological end point was abnormal larvae, defined as those larvae which had incompletely developed shells 48 hr after fertilization. Nelson's results are illustrated in Table 3, which shows that there were significant increases in abnormal larvae in ^{65}Zn solution (carrier free) at a concentration of 10^8 pCi/liter and greater, in ^{65}Zn solution (with carrier) at a concentration of 10^7 pCi/liter and greater, in ^{51}Cr solution at a concentration of 10^8 pCi/liter and greater (stable chromium had no effect at any of the levels tested), and in $^{90}Sr-^{90}Y$ solution at a concentration of 10^9 pCi/liter.

On the basis of these experiments, Nelson concluded that the concentration of $^{90}Sr-^{90}Y$ necessary to produce abnormal oyster larvae (10^8 pCi/liter) is 10^7 times greater than the maximum concentration of ^{90}Sr in natural marine environments (10 pCi/liter), as reported by Miyake and Saruhashi.[19] The concentration of carrier-free ^{65}Zn necessary to produce an effect on oyster larvae in the first 48 hr after fertilization of the eggs is 10^7 times greater than the ^{65}Zn concentration in Willapa Bay. Concentrations of ^{51}Cr which caused demonstrable effects are 800,000 times greater or more than those reported in water collected between the mouth of the Columbia River and Willapa Bay in 1961, when all eight Hanford production reactors were still in operation. Since then, six of these have been shut down.

Table 3 Mean Percentage of Abnormal Pacific Oyster Larvae 48 hr After Fertilization at Various Concentrations* of $^{90}Sr-^{90}Y$, ^{65}Zn (Carrier Free), ^{65}Zn (with Carrier), and ^{51}Cr

Radioactivity concentrations in seawater		$^{90}Sr-^{90}Y$			^{65}Zn carrier free			^{65}Zn with carrier			^{51}Cr		
		No. of lots	Abnormal larvae, %		No. of lots	Abnormal larvae, %		No. of lots	Abnormal larvae, %		No. of lots	Abnormal larvae, %	
pCi/liter	pCi/cm^3		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation
Control		15	8.5	2.5	9	7.7	2.2	10	8.6	4.1	12	6.8	1.4
10^6	10^3	6	8.3	1.6	4	9.0	4.2	6	9.3	2.6	6	7.5	3.7
10^7	10^4	2	5.5	0.7	3	21.7	15.0	2	43.5	6.4†	5	9.2	1.8
10^8	10^5	7	11.0	2.7	5	28.0	9.9†	4	32.7	10.7†	6	16.3	6.9†
10^9	10^6	4	98.0	0.8†	2	100.0	0†	2	100.0	0†	6	26.3	3.1†
10^{10}	10^7	4	95.8	2.1†	1	100.0	0†	3	100.0	0†	3	56.7	35.7†

*From Ref. 18.
†Significant at 5% level.

Effects of Diluted Hanford Effluent on Salmon

The possibility of biological effects of the effluent from Hanford production reactors has been investigated for over 20 years by raising salmonid fish in the diluted effluent. The three main factors in the potential pollution effects of Hanford reactor effluent on fish are thermal increment, radioactivity, and chemical toxicity, since hexavalent chromium was used as a corrosion inhibitor.[17] Freshly fertilized eggs of salmonids were incubated, and the fish were raised in various concentrations of effluents until they reached migrant-sized fingerlings. Table 4 shows the mortality, growth, and radionuclide concentration in chinook salmon raised under various effluent conditions.

Table 4 Mortality, Growth, and Radionuclide Concentration in Chinook Salmon, *Oncorhynchus tshawytscha*, Reared Under Various Reactor Effluent Conditions from December 1965 to April 1966 at Hanford*

Treatment Group: At Least 1000 Fish

Reactor effluent in environment, %	Fish mortality in 5 months, %	Fish mean weight, g	Radionuclide concentration, pCi/g wet weight		
			^{24}Na	^{51}Cr	^{65}Zn
0	18	0.70	77	19	6.8
2	10	0.82	750	38	20
4	13	1.05	1390	53	36
6	13	1.20	2210	65	45

*From Ref. 17.

No significant lethality occurred in 6% effluent, a concentration far above the existing levels in the Columbia River. The greater growth observed in fish maintained in effluent is due to the heat in the effluent, which accelerates growth. The concentrations of the three gamma emitters, ^{24}Na, ^{51}Cr, and ^{65}Zn, in the fish were approximately proportional to the effluent concentration. The investigators point out that the body burdens at these levels produced no demonstrable damage in chinook salmon.

Effect of Low Concentration on Marine Fish Eggs

No review of this nature can forego mention of Russian work in this field, especially since the Russians have reported some effects at much lower concentrations of radionuclides than other workers. Russian emphasis has been placed on marine fish eggs. Polikarpov,[20] who pioneered the studies in this field, has reported on extensive studies with eggs on a large number of marine and freshwater species over the concentration range 10^{-2} to 10^8 pCi/liter. He reported reduced hatching of larvae and early mortality at concentrations of 10^5 pCi/liter and above, and the number of abnormalities increased significantly at concentrations of 10^2 pCi/liter and above with remarkable consistency.

British workers[17] performed similar experiments with eggs of two fish species maintained from immediately after fertilization until hatching in water contaminated with ^{90}Sr–^{90}Y over a concentration range of 10^2 to 10^8 pCi/liter. No significant increase in mortality or in the production of abnormal larvae was observed.

Templeton, Nakatani, and Held[17] point out that the particular significance of the work from the USSR is the unique concentration effect reported by Polikarpov[20] in 1967. An increase in concentration over six orders of magnitude (from 200 to 200 million pCi/liter) no more than triples the abnormality production rate and only increases mortality fivefold. This result is inconsistent with the linear hypothesis of dose response, as well as with data from many radiobiological investigations.

Effect of Tritium on Fish Eggs

Preliminary experiments of the effect of tritium on fish eggs are under way at Oak Ridge National Laboratory (ORNL) and at the University of Washington. At ORNL, Blaylock[21] has subjected fertilized carp (*Cyprinus carpio*) eggs to various concentrations of tritiated water. The biological end point was hatchability that normally occurs at 72 hr when maintained at 26°C. Since the embryonic stages are considered among the most sensitive stages of the life cycle to irradiation, this was considered a useful method for testing the effect of tritiated water. An additional advantage is that the eggs imbibe water and swell. Assuming no discrimination against tritium, the eggs would be exposed to both external and internal doses from tritium. The concentrations used ranged from 6.75×10^7 to 51.8×10^7 pCi/cm^3 (Table 5).

Table 5 Hatchability of Carp Eggs in Different Concentrations of Tritiated Water*

Tritium concentration, μCi/cm^3	Accumulated dose in 72 hr, rads	Total number of eggs	Eggs hatched, %
0	0	436	93.1
67.5	57	285	85.6
127.0	107	293	86.6
274.0	231	474	85.9
375.0	316	408	93.4
518.0	436	257	92.6

*From Ref. 21.

These concentrations delivered a 72-hr dose to the eggs and developing embryos of from 57 to 436 rads. Although the percentage of eggs that hatched was less in three of the concentrations than in the controls, statistical tests showed no significant differences between any of the doses and the controls.

At the University of Washington,[22] hybrid trout eggs were exposed to tritiated water at concentrations ranging from 10^9 to 10^{11} pCi per liter of water. No significant differences between groups were observed. The investigators are repeating the experiments with a 100-fold increase in the highest concentration (10^{13} pCi/liter). These workers also tested the effects of tritiated seawater on spore germination and sporling development of the algae *Padina japoinia* Yamada. Effects on germination and subsequent growth were observed only at the highest concentrations of tritium used (3×10^{10} pCi/liter). Admittedly these tritium experimenters have not followed up on any possible delayed effects after the fresh eggs hatched. Nevertheless, no effects on fish eggs resulted at concentrations up to 100 million times greater than MPC levels, but effects on algae did result at concentrations 10 million times greater than MPC levels.

CONCLUSIONS

What inferences may be drawn from these data? The response of research workers in such situations is frequently that there is insufficient information and that more research is needed. As a scientist, one is not entirely immune to this special type of bias. To call for such research is easy; to attract first-rate scientists to devote years of their professional lives to experiments wherein the outcome may be the production of consistently negative results is not so easy. Journals are not interested in publishing such data. Moreover, one might question whether the investment required could not be put to better use in other research areas.

These data, as well as many others that I have not mentioned, with the possible exception of Russian data, show that the dose necessary to evoke an unequivocally detectable biological response is considerably above that resulting from MPC concentrations in the environment.

Templeton, Nakatani, and Held[17] provide some pertinent viewpoints on the genetic effects. "The genetic consequences of radiation exposure have been and are still being studied very extensively in connection with the potential hazards to man. In general the conclusion from these studies is that any significant increase in radiation levels is detrimental from the genetic point of view. However, for man, this acceptance rests on ethical considerations, which take note of the individual, and the fact that genetic anomalies are not reparable in an individual. When considering the marine environment, however, we are not concerned with individual organisms, but with populations, and at the population level, genetic damage is reparable by natural selection."*

A similar viewpoint has been expressed by Purdom,[23] a British worker in this field. "It would seem likely that the genetic response of populations is relatively unimportant and that general mortality and infertility would be the limiting factors in the extent to which populations may overcome radiation exposure. This certainly seems true for animals which have been studied extensively—*Drosophila*, the mouse, and domesticated farm animals. Provided that marine organisms are not more sensitive genetically than these other organisms, genetic damage will probably have negligible effects, even under the maximum radiation exposures that seem possible from present day practice."

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*Natural selection is the agent of evolutionary change by which the organisms possessing certain characteristics in a given environment give rise to more offspring than those lacking such characteristics.

On the basis of the present state of knowledge, it is not unreasonable to infer also that low dose rates (at or around MPC levels) delivered to ecosystems under field conditions may present a problem of such technical complexity that for practical purposes it may be technically intractable. At present our best technologies and methods cannot demonstrate effects to these systems at these doses that are clearly and uniquely attributable to ionizing radiation. On the other hand, our knowledge, as well as the research on which it is based, is limited. The possibility of developing sufficiently sensitive methods exists but will undoubtedly require superbly well-controlled laboratory conditions.

One might invoke special effects on organisms with undefined or special roles in the ecosystem which make them uniquely sensitive (and therefore the ecosystem also) to the low dose rates that might occur in the vicinity of nuclear power stations. The possibility exists that the radiosensitivity of organisms may be increased significantly as a result of environmental interactions. Ecologists are always seeking some unusual effect or a species with high sensitivity to ionizing radiation. Thus far no organisms have been found which, within an environmental context, have a radiosensitivity at the levels of release permitted under current standards. Research is continuing to include as many different kinds of organisms as possible from a variety of environments (habitats) to demonstrate and differentiate the effects of radiation within an environmental context.

All the foregoing suggests essentially the same answer to a question posed at the recent Burlington, Vt., public-education meeting. That is, if MPC_w levels of radionuclides have an effect on the biota living in the vicinity of nuclear stations, these effects will be essentially undetectable. The reason for this judgment lies in the fact that there undoubtedly would be other factors changing in the environment or other substances added to the aquatic environment which may and undoubtedly will have an effect on the constituent organisms. These substances (chemicals, nutrients, etc.) may modify the habitat and affect the constituent organisms present to the extent that it will be extremely difficult, using current methodologies, to demonstrate effects that might result from the low levels of radioactivity.

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NUCLEAR ENERGY: BENEFITS VERSUS RISKS

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Just a few years ago almost everyone looked forward to the coming age of nuclear energy as a boon to mankind. Of course the coal interests have always been less than enthusiastic, but that was to be expected. Recently, however, many persons have undertaken the role of professional critics, joined by some conservationists.

I feel particularly betrayed in this instance, for I have long considered myself a conservationist. Certainly one of my strongest motives in promoting nuclear energy has always been the conserving of our valuable and irreplaceable fossil fuels, coal, oil and gas. Because this can be accomplished and, at the same time, the pollution of our atmosphere reduced, I felt a sense of righteousness in promoting nuclear energy. But these critics say that all these fine benefits just are not worth the risk. I strongly disagree. I believe that more lives have already been saved by the advent of nuclear energy than will be lost as a consequence of it in the next hundred years.

A swarm of controversy over the growing nuclear technology appears to be developing. If it were just an occasional book or article, I would be inclined to hold my peace. Unfortunately, it is deeper than that. Part of the federal licensing procedure for a nuclear-power plant, though not for any other kind, stipulates that a public hearing be held at which individuals may intervene. In some cases these hearings have been so drawn out that the power company has withdrawn its application rather than face the continued publicity. A power plant planned for construction at Bodega Bay, Calif. has been abandoned. The opposition was concerned mainly with the natural beauty of the proposed site, but the issue of earthquake damage was the deciding factor. New York State Electric & Gas Co has decided to postpone indefinitely the project to build a nuclear-power plant at Ithaca. In this instance the intervenors protested the possible thermal pollution to Cayuga Lake.

Electrical power, polluted air

First, let me summarize some of the benefits. I do this quickly because there really is not much argument about this part. The real reason that power reactors are being installed in so many places in the US (some 80 nuclear-power plants have been ordered; 15 are in operation) is to save money. Although construction costs of a nuclear plant are higher than those for a fossil-fueled plant, the operating costs are much less. As a consequence the cost of electricity will be less than it would have been with fossil-fuel plants.

The demand for electricity has almost doubled within the past ten years, and another doubling is projected for the next decade. Part of this rise is caused by the population increase, but for the most part it reflects a higher

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standard of living. When I came to Oak Ridge National Laboratory some 20 years ago, air conditioning was a rarity. Now the summer demand for electricity in some regions exceeds the winter demand. Although nuclear energy is beginning to supply some of the ever increasing demand for power, the fossil fuels (coal, oil and gas) are being burned at an ever increasing rate. Moreover our reserves are very limited. Whether the commercial supply of them will be exhausted in 50 years or 200 years is not certain-but the time is short compared with the already brief span of man's existence on this planet, or with the hundreds of millions of years that it took to form those deposits of coal and oil. Our limited reserves are fast going up in smoke.

And smoke there is! From a single large, coal-fired power plant, such as Bull Run near Oak Ridge, hundreds of tons of noxious sulfur oxides are emitted every day. In addition to the sulfur, thousands of tons of carbon dioxide are emitted by Bull Run per day. (It has been observed that the carbondioxide concentration in the atmosphere is increasing at about 2% per decade, a change that may have implications for long-term effects on climate.) No longer is the air clean and pure in the Tennessee Valley - or in New York, or in Los Angeles, or indeed in most of the US. Our eyes may burn, and pine trees drop their needles.

Unfavorable atmospheric conditions can be so bad that many people sicken and die as they did in Donora, Pa., in 1948 (43% of the population became ill, 20 deaths attributed to smog), or in London, England, in December 1952, when the excess fatalities were estimated at 3500.[1] (There was a time in English history, around 1300, when King Edward I decided to take steps toward reducing pollution. He made it a crime punishable by death to burn coal.)

It is imperative that we take steps to reduce this outpouring of noxious gases either by removing them from the smokestacks, thereby increasing the cost of electricity, or by installing nuclear-power plants. Coal-fired power plants are not the only contributors to the air pollution of the country: Automobiles and trucks also represent a major source, as does the heating of homes and buildings. To reduce this pollution caused by combustion, a general conversion to electricity will have to ensue. Homes must be heated electrically and automobiles and trains driven electrically, which will triple the demand for electricity, a challenge that can only be met economically with nuclear-power plants.

Nuclear power offers a virtually inexhaustible supply of cheap electricity. Moreover, it offers a chance to clean up the atmosphere. But there is, in addition, a third major benefit-the myriad uses of radioisotopes. These isotopes, produced so copiously in every nuclear-power plant (and indeed representing the chief danger in their operation), have already proven to be a great boon to mankind. Although production reactors have been the chief source of the fission-product radioisotopes, such as Sr^{90} and Cs^{137}, power reactors will undoubtedly become the major producers in the future. Research reactors and cyclotrons supply most of the medical isotopes. Estimates of the benefits of these isotopes to industry are of the order of a $1000 million a year. Many major industries use radioisotopes to gauge the thickness of sheet steel in a rolling mill; the level of a liquid in a tank or the flow of oil through a pipeline is measured with radioisotopes. Isotopes are also used for well logging in the exploration for oil. A slow leak in a water main or a gas line can be found with an isotopic tracer. The gamma rays from Co^{60} are used for "x raying" welds and are used in a chemical plant to produce new plastics. The dramatic uses of radioisotopes in agriculture, biology and medicine have caught everyone's attention.

Daily hazards

I could easily lecture for many hours about the benefits of nuclear energy. However, there are also risks. Those radioactive isotopes that are so useful when properly prepared also represent a major hazard. The possibility, no matter how remote, of spreading millions of curies of radioactivity over the countryside is not a pleasant one to contemplate. The critics present a gloomy picture. How likely is such an accident? Before discussing that question, let us recall some risks that we all encounter in everyday life[2,3] (see Table 1).

Table 1. Risks in Daily Life*

Type of Risk	Death rate per 10^6 hrs of exposure
Riding in a private car (US)	0.95
Riding on railroads and busses	0.08
Flying on a scheduled airline	2.4
Riding a motorcycle	6.6
Death due to disease, old age	1.0
Smoking cigarettes	1.2
Rock climbing	40.0
Radiation at a rate of 5 rem/yr (extrapolated linearly from experiments at high-dose rate)	0.05

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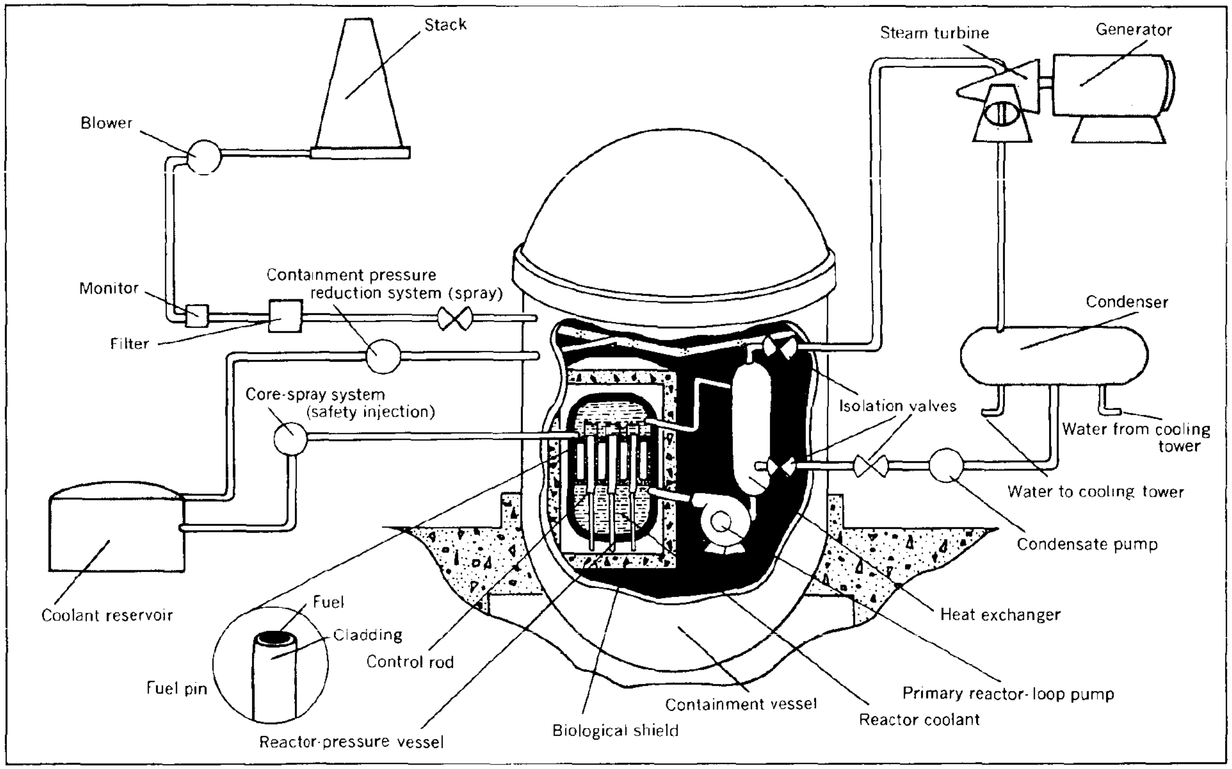
* Data from reference 3.

To get a feeling for the numbers involved, consider the probability that an average member of the population will die during the next hour due to disease, such as heart failure and cancer. The figure is about one in a million, or probability $P = 10^{-6}$ hour^{-1}.

It appears that people are willing to accept a risk of about that same magnitude provided it is voluntary and the benefits are personal and real. For example, the risk of being killed while riding in a car is about 10^{-6} per hour of exposure, about one-tenth of what it was a generation ago. There have indeed been significant advances in automobile safety. The risk of riding in a commercial airplane is now about 10^{-6} per hour, which means that air travel is some ten times safer than auto travel on a mileage basis because planes travel so much farther in an hour. Air travel in private planes is a much more dangerous undertaking; fatalities in these flights are some 20×10^{-6} per hour of exposure, 20 times more risky than commercial air travel. And yet many people willingly take the risk of their own free will. No one imposes the risk upon them.

On the other hand, if the risk is imposed upon a person (such as an airplane falling on a busy street, or the explosion of gas mains in a city,) he will insist that the probability of death be much less than the normal disease death rate. He will live below a dam, if he is convinced that the chance of the dam collapsing is very remote (perhaps 10^{-8} per hour of exposure) and that there is good reason (benefit) for him to live with the exposure to a small, but not zero hazard. He may protest if a chemical plant or a nuclear-power station is built near his home - suggesting that it be built in another location - but if he is convinced that the risk is small, he will not move. A small risk is, as we have assumed, something less than 10^{-8} per hour of exposure or 10^{-4} per year. In other words, if he is convinced that a major catastrophe will happen only about once in every 10,000 years, he will feel that the risk is acceptably small. Will Los Angeles and San Francisco be



SAFEGUARDS IN A NUCLEAR-POWER REACTOR. The fuel cladding, the reactor vessel and the containment vessel are the three major barriers that prevent the escape of fission products.

spared a major earthquake for that long? Less than 50 years ago 150,000 people were killed in Japan as a result of an earthquake.

Nuclear risks ...

Only by experience can we demonstrate that the risk of living near a nuclear plant is small. The situation is indeed remarkably similar to the budding electric-power industry in the latter part of the last century. There was a great deal of opposition to the introduction of electricity into the home. The critics pointed out that electricity was dangerous, that people would be electrocuted, that innocent children would stick their fingers into electric sockets and die a horrible death and that wires would become overheated and burn down the homes. Of course they were right. A thousand people in the US are accidentally electrocuted every year. Moreover, it has been estimated that 16% of the fires are electrical in origin and 1200 Americans lost their lives last year in these fires. However, there are 200 million people in the US, so the individual's chance of being killed is small, about 10^{-9} per hour of exposure. This is well below the "acceptable" risk of 10^{-8}, and the benefits of electricity are so apparent to everyone that no one wants to turn back the clock.

Let us now turn to the risks of operating nuclear-power plants. These can currently be classified as:

Thermal pollution of the rivers and lakes, also known as thermal effects.

Low-level release of radioactivity into the air and ground waters caused by the normal operation of nuclear-power and reprocessing plants.

The accidental release of large amounts of radioactivity.

To my mind this last item is the risk causing the most concern, but the critics (Chauncey Starr calls them "nuclear hypochondriacs") have been equally vociferous about the first two items.

Thermal pollution is not a new phenomenon, nor is it confined to nuclear-power plants. Many industrial plants generate a large amount of heat, and it is much less expensive to dump the waste heat into a river than to release it to the atmosphere. The rivers that flow through Pittsburgh, for example, are raised in temperature by 20 or 30 deg. This has had an adverse effect on the fish and has in general upset the ecology. Federal standards are needed, and enforcement by the states is most desirable. Such legislation is now pending in Congress. These regulations should apply to any plant, be it nuclear, fossil-fueled or chemical. Nuclear plants should conform no more or no less than any other type. It is true that a nuclear electric plant dumps more heat into a stream than a fossil-fueled plant of corresponding electric-power output. But it does not make sense to raise a storm of protest over a nuclear plant of 500 MW electric capacity while a 1000 MW electric fossil-fueled plant escapes almost unnoticed. New York State has passed legislation requiring nuclear plants to make an environmental-evaluation report, which is not required for conventional plants.

It is not surprising that a nuclear-power plant that generates millions of curies of radioactivity may discharge a very small amount of radioactivity into the atmosphere or waste stream. The whole argument has to do with defining a "small amount" of radioactivity. The nuclear critics insist that it should be zero for a nuclear plant, whereas they recognize that a coal plant does emit some radioactivity from the small amount of uranium and its daughter products in the coal.

Merril Eisenbud and Henry G. Petrow[4] have noted that although the amount of radioactivity from a large coal-burning power plant is less than 1 curie per year of Ra^{226} and Ra^{228}, this release is the equivalent of considerably greater amounts of I^{131} and Kr^{85}, which are the principal atmospheric effluents from a nuclear-power plant. In either case the radiation dose to the nearby population is very small compared to the natural background of radioactivity.

...from radiation effects

Actually we know much more about the effects of radiation on the human body than we do about the effects of various chemical pollutants that occur in ever increasing amounts in the air we breathe and the water we drink. Hundreds of millions of dollars have been spent by the Atomic Energy Commission in biological research aimed at establishing not only the effects of radiation on man but also on the environment, so we can be certain that the ecological effects will be minimal. This concern is almost without precedent. Certainly the automobile industry has not expended much money on the effects of smog on the population, or the tobacco industry on lung cancer or the chemical industry on the effects of DDT on the ecological cycle. One of the nuclear critics' favorite expressions is that there is enough radioactivity in a reactor to irradiate everyone in the US with a lethal dose. There is also enough insecticide manufactured to poison every US citizen; moreover, the insecticides are meant to be widely distributed, yet the radioactivity is carefully confined.

As a result of the tremendous research effort on the effects of radiation, the Federal Radiation Council has developed a set of radiation-protection guides. The levels that have been set, even for workers in the nuclear industry, are meant to be at least an order of magnitude below that where physical effects on the individual would be observed. (This is in contrast to the ozone level in Los Angeles, which is set just barely below the level where eye irritation will be noticed.)

If workers in the nuclear industry were to get the maximal level of 5 rem per year, there probably would be a small increase in the observed number of deaths caused by leukemia after a number of years. But the additional risk of death by leukemia to each person so exposed would be less than 10^{-8} per hour of exposure, less than the normal occupational hazards.[5] Actually, it is rare for anyone to get 5 rem during a year, and most of us get much less. Although 5 rem is considered to be a conservative figure (much less, for example, than radiologists used to take) it is thought that an additional factor of 30 reduction should be made when considering the dosage levels to the population at large. Hence the protection guides limit the amount of activity to such a low level that the general population will receive no more than a fraction of a rem per year. Everyone receives something like a tenth of a rem per year of radiation because of cosmic rays and natural radioactivity in the earth and air-everyone, that is, but those who live in certain high-level radiation areas, like India, where they receive eight times as much.

When one adds to this the radiation from medical x rays (estimated to be another 0.1 rem to the average member of the population), it is apparent that the amount contributed by nuclear power is small in comparison. I do not hesitate to take several rem of x rays when it is needed for diagnosis or treatment of disease. Here is a very real example-the benefits far outweighing the risks. On the other hand, I am opposed to taking even a medical x rays needlessly. Some of the older machines for dental x rays sprayed the whole body; the use of a filter and cone can produce better pictures with less radiation. X-ray machines in hospitals have also been greatly improved; good, clear, lung radiograms can be obtained with a dose of one-tenth to one-hundredth of a rem rather than with the several rems required with poor equipment and procedures.

Recent measurements by the Bureau of Radiological Health, Department of Health, Edication and Welfare, have shown that the Dresden Nuclear Power Station, Ill., has contributed a negligible amount of radioactivity to its environs, something less than 1% of the natural radioactive background and orders of magnitude below permissible limits. But despite the conservatism in setting the federal radiation-protection guides, the Minnesota Pollution Control Agency, responsible for water purity, has recently protested the granting of a license to operate a reactor, unless the operator guarantees to maintain a level of activity release that is a factor of 100 below the values recommended by the Federal Radiation Council. If the utility is not granted a license to construct a nuclear-power station, power demands will have to be met by adding fossil-fuel stations with all the stack effluents. All in the name of "safety." I believe it is demonstrable that the hazard from the presently regulated amount of radioactivity released in normal operation of a nuclear-power station is much less than that from the pollutants emitted by the operation of a fossil-fueled station.

Safeguards

However, the risk of releasing a large amount of activity inadvertently is quite another matter. The hypothetical consequences of such an accident were the subject of a much publicized Brookhaven National Laboratory report some ten years ago. The authors assumed the worst possible combination of circumstances. They gave no credit for containment in estimating that half of the fission products would become airborne; they assumed that the accident would occur during an atmospheric inversion and low-wind velocity; and thus the fission products would be carried straight toward a population center with very little dilution or mixing. Under these catastrophic, but unlikely, circumstances up to 3000 people could be killed, assuming evacuation was not possible. The possibility that such a major catastrophe will occur is, I believe, exceedingly remote. However, the occurrence of several smaller events is certainly within the realm of possibility; there surely is some risk. Nevertheless, it is the stated mission of the nuclear industry and the regulating agency to make the possibility of such an accident exceedingly remote. How do we go about it?

First, the fission products are contained in fuel elements that would melt only if cooling were to fail. Second, the fuel elements are contained within a primary coolant circuit that undergoes the most thorough series of tests and inspections that any pressure vessel has ever been subjected to. Then the whole works is contained within a large steel or concrete containment vessel. Finally, there is an exclusion area surrounding the power plant and a low-population zone outside of that. This should result in considerable dilution of the radioactive fission products before they reach the population center, as well as introduce a delay so that evacuation can begin.

For the radioactive fission products to escape, the fuel elements must melt, the primary vessel must burst and the containment vessel must fail. Even if all these failures occurred, it appears that probably to more than 5% of the fission products would become airborne-rather than the 50% assumed in the Brookhaven report. Even so, the release of 5% of the radioactive products under unfavorable atmospheric conditions would be serious. And we can see ways that it might happen. However, bear in mind that, when a mechanism for an event can be postulated, the design can be modified to make that particular mode of occurrence most unlikely. It is true that fate has a way of figuring out another path to an incident that was not foreseen. But the designers and builders of nuclear-power plants have exercised sophisticated ingenuity and have spent large sums of money to make the plants as safe as they know how.

There have been accidents and releases from experimental reactors.[6] The releases have been small by comparison with the hypothetical Brookhaven incident, and no member of the public has been injured. The graphite moderator of a large reactor in Windscale, England, caught fire, causing some fuel elements to melt and burn. A considerable amount of radioiodine was spread over the countryside, thereby contaminating milk supplies and crops. That reactor was not in a containment vessel (all nuclear-electric stations in the US are contained), so perhaps 2% of the fission products did escape. No power reactor in the US has been similarly involved. There were some fuel elements melted in the Fermi reactor, but neither the primary nor the secondary containment was violated.

A small experimental army reactor (SL-1) released a considerable amount of radioactivity to the building where it was operated, but only a relatively small amount of activity, an estimated 80 curies of I^{131}, escaped from the building and precipitated on the desert. The prophets of doom have heavily dramatized these reactor incidents, pointing out that it can happen despite our best efforts. It all depends on your point of view. To me it demonstrates that a fairly major release of radioactivity from the core can occur, as at Windscale or SL-1, and yet no one outside the reactor building received a tolerance dose of radiation.

The important question still remains. Have we succeeded in reducing the risk to a tolerable level, that is, something less than one chance in ten thousand that a reactor will have a serious accident in any year? When we have one hundred nuclear-power stations in operation, which is not too far in the future, an accident once every hundred years might be expected. And if a hundred people were to be killed, such as now happens in a major airline disaster, it is a lower calculable risk than that taken by many facets of US industry today, and a small price to pay for the benefits.

Have we succeeded in reducing the hazards to such a low level? There is no way to prove it. We have accumulated, so far, some 100 reactor years of accident-free operation of commercial nuclear electric power stations in the US. That is a long way from 10,000, so it does not tell us much.

The only way we will know what the odds really are is by continuing to accumulate experience in operating reactors. There is some risk, but it is surely worth it. I am impatient with those who cry "wolf" when there is so much to be achieved. On the other hand, it is a mistake to use the head-in-the-sand approach and say it can never happen to us. Scientists and the public should be prepared to face the possibility of a nuclear incident just as we expect major earthquakes that will exact a large toll in property and lives. Only a few people advocate abandoning the West Coast. I hope only a few advocate abandoning nuclear power, which promises so much for mankind.

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RADIOECOLOGY AND THE FEASIBILITY OF NUCLEAR CANAL EXCAVATION[1]

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Abstract. As a prime contractor to the Atomic Energy Commission, Nevada Operations Office, the Battelle Memorial Institute, Columbus Laboratories, is responsible for the technical management of bioenvironmental and other studies to help judge the radiological-safety feasibility of nuclear-excavation plans for the construction of a sea-level canal across the isthmian region of Central America. As part of the program to predict external and internal radiation doses to human populations living in the vicinity of the proposed canal routes, extensive field studies of human, agricultural, forest, freshwater, and marine ecology have been undertaken by different subcontractor groups in eastern Panama and northwestern Colombia. The results of these studies, which will not be completed until June, 1968, will be combined with predictions of radionuclide production and initial fallout distribution to develop methods of estimating radionuclide transfer through tropical food chains and other environmental pathways leading to man. Estimates will be made of the kinds and quantities of radionuclides to be expected, during and after nuclear excavation, in the external environments and diets of native populations in different parts of the two study areas, and calculations of potential radiation doses to man will be based on these estimates. Owing to the nature of the problem and to the virtual absence of previous ecological studies in the area of concern, it has been necessary to make broad ecological studies of a fundamental nature. This paper reviews the progress of these studies to date and demonstrates that the assessment of potential radiological hazards in relation to nuclear-excavation projects is dependent upon the accumulation of ecological and biogeochemical data and the application of radioecological principles.

Introduction

One objective of the U.S. Atomic Energy Commission's Plowshare Program has been the development of technology for the use of nuclear explosives in massive excavation projects. Experiments performed as part of the Plowshare Program have led to the development of devices and techniques which minimize the production and release of radioactive materials and to the establishment of scaling factors which can be used in solving the attendant engineering problems. The state of the art is now such that it is quite reasonable to consider a variety of excavation projects in which nuclear explosives could be used economically and safely. The most interesting of the potential nuclear-excavation projects that has received serious study in recent years is the proposal to construct a sea-level canal connecting the Atlantic and Pacific Oceans.

The need for such a canal is clearly indicated by the growing limitations imposed by the very nature of the present Panama canal. For example, there are 74 naval and commercial ships presently in operation that are too large to fit in the locks of the present canal but which could pass through a sea-level canal quite easily. There are some 550 commercial ships that cannot pass through the locks when they are fully loaded, and the trend is to build even larger ships because they are more economical to operate. An even more serious limitation is imposed by the fact that each ship transit requires a considerable volume of water for the operation of the locks. Recent studies have indicated that the limit thus imposed by the availability of water in Lake Gatun is

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[1] Studies being performed under Contract No. AT(26-1)-171 for the Nevada Operations Office of the U.S. Atomic Energy Commission.

Martin, W. E. 1969. Radioecology and the feasibility of nuclear canal excavation. pp. 9-22. In: Symposium on Radioecology. (D. J. Nelson and F. C. Evans, eds.). U.S. AEC report CONF-670503.

approximately 19,000 transits per year. In recent years there have been more than 12,000 transits annually, and, if the traffic on the canal continues to increase at the postwar rate, the average transit time will increase steadily, cause expensive delays, and the number of ships desiring to use the canal possibly will exceed the limitation of 19,000 transits per year. Other advantages of a sea-level canal as opposed to a lock canal are that the former would be less expensive to operate and maintain and easier to defend from possible attack.

Sea-Level Canal-Feasibility Studies

A joint study completed in 1964 by the U.S. Army Corps of Engineers, the U.S. Atomic Energy Commission, and the Panama Canal Company considered over 30 possible routes for a sea-level canal and recommended that more detailed studies be made of two routes, the Sasardi-Morti route (Route 17) in Panama and the Atrato-Truando route (Route 25) in Colombia, where nuclear excavation might be accomplished. The same study provided an estimate that the cost of converting the present lock canal to a sea-level canal by conventional construction methods would be approximately $2,176,000,000, while the estimated cost of nuclear excavation was $747,000,000 for the Sasardi-Morti route and $1,440,000,000 for the Atrato-Truando route (Fig. 1).

In April of 1965, President Lyndon B. Johnson appointed five men[2] from private life to constitute the Atlantic-Pacific Interoceanic Canal Study Commission and authorized them "to make

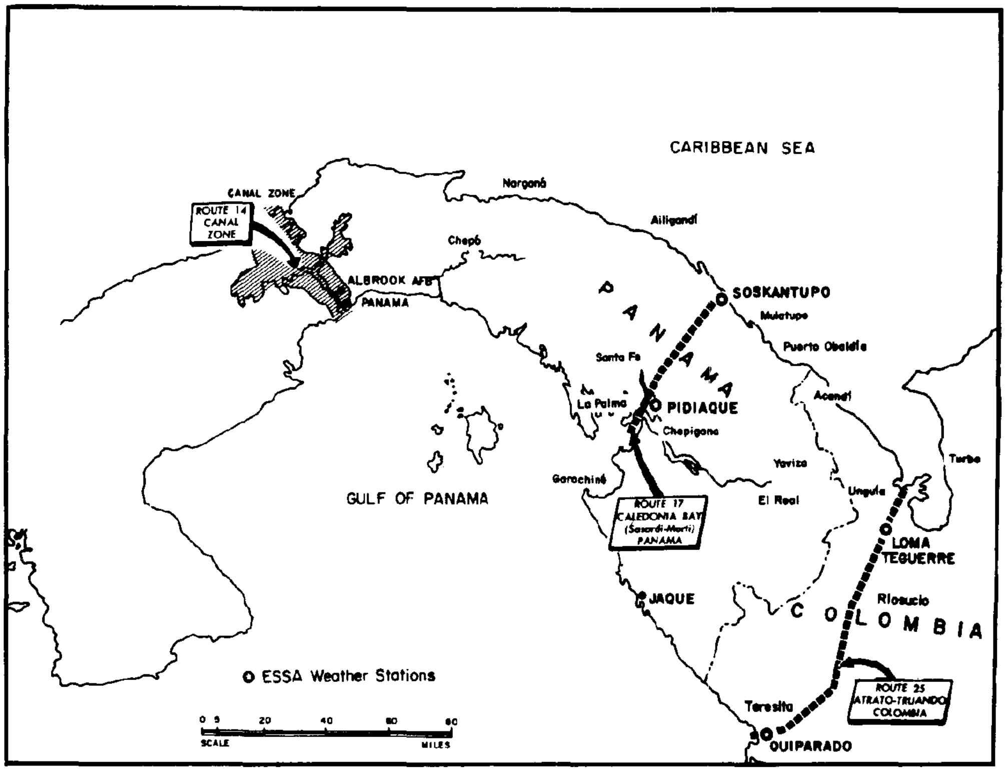

Fig. 1. Possible sea-level canal routes.

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[2] Mr. Robert B. Anderson, Chairman, Mr. Robert G. Storey, Dr. Milton S. Eisenhower, Brig. Gen. Kenneth Fields, Ret., and Mr. Raymond A. Hill.

a full and complete investigation and study, including necessary on-site surveys and considering national defense, intercoastal shipping, interoceanic shipping, and such other matters as they may determine to be important, for the purpose of determining the feasibility of, and the most suitable site for, the construction of a sea-level canal connecting the Atlantic and Pacific Oceans: the best means of constructing such a canal, whether by conventional or nuclear excavation, and the estimated cost thereof."

Under the auspices of the Atlantic-Pacific Interoceanic Canal Study Commission, study groups were established in the Departments of State, Defense, Commerce, and Treasury to consider, respectively, problems related to foreign policy, national defense, interoceanic and intercoastal shipping, and canal finance. On-site surveys to determine the engineering feasibility of the nuclear-excavation plan and the plan for conversion of the existing canal to sea-level operation have been made by the U.S. Army Corps of Engineers. Studies related to the operational-safety feasibility of the nuclear-excavation plan are considered to be a part of the engineering feasibility program, and the necessary on-site surveys have been made by contractors to the U.S. Atomic Energy Commission, Nevada Operations Office.

It is not within the scope of this paper to discuss the entire feasibility study, but a brief outline of the on-site surveys will help to place the bioenvironmental studies in perspective. The U.S. Army Corps of Engineers has made on-site studies of topography, geology, hydrology, and hydrography. Detailed information concerning topography and geology is needed to determine the precise spacing, depth, and yield of nuclear explosives required to produce the desired canal configuration and to evaluate various other engineering problems. Data related to hydrology and hydrography are necessary, for example, to determine whether or not it might be necessary to divert natural drainage to avoid flooding the canal and whether special structures might be needed to control tidal currents near the ends of the canal. The program related to the operational-safety feasibility of the nuclear-excavation plan includes studies of the potential effects of ground shock and the long-range transmission and ducting of acoustic waves on man-made structures. The Environmental Sciences Service Administration is making the meteorological studies required to predict fallout patterns and acceptable shot days. The bioenvironmental studies related to radiological-safety feasibility are being made by various subcontractor organizations under the management of Battelle Memorial Institute, Columbus Laboratories.

At the present time (March, 1968) these feasibility studies, including a study by the Surgeon General's Office to determine the occurrence of human diseases and vectors in the areas of the proposed canal routes, are still in progress and the deadline for the Canal Commission's final report to the President has not been firmly fixed. Consequently, the following report will, of necessity, be no more than a very abbreviated progress report with only a brief description of the nuclear-excavation plan, a few comments on the major problems related to radiological-safety feasibility, and a short review of the ecological field studies being made under Battelle management.[3] Since the technical results and conclusions of these studies are not available at the present time, it will be necessary to concentrate on the general concepts and objectives of the studies involved.

General Concept of the Problem

Details of the nuclear-excavation plan will, of course, depend on the results of on-site surveys in Panama and Colombia and Plowshare experiments in the United States, but the general idea is to excavate the canal by segments. Alternate segments would be excavated on the first pass, and on the second pass those segments would be joined by another series of detonations. Each segment would be excavated by the simultaneous detonation of from 3 to 50 devices buried in a row along the desired alignment. The final step would be the opening of terminal segments by conventional means. Preliminary studies indicate that some 200 to 300 devices, ranging in yield from 0.2 to 10 megatons each, would be required. For Route 17 in Panama there would be 21 detonations of approximately 10 megatons each and one detonation of about 30 megatons to cut through the continental divide. Depending on the alignment selected, the length of canal to be excavated by nuclear means would range from 40 to 48 miles. (Only the southern part of Route 25 would be excavated by nuclear means.) The total yield of the nuclear explosives would be between 200 and 300 megatons, which is more than the announced total yield of all nuclear devices thus far detonated by the U.S.

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[3] A special Symposium on Sea-Level Canal Bioenvironmental Studies will be offered at the AIBS meetings September 1- 7, 1968, at Columbus, Ohio.

The indigenous populations living near the proposed canal routes in Panama include Negroes and other Spanish-speaking people, Choco Indians, and Cuna Indians. Preliminary demographic data indicate that no more than 25,000 or 30,000 people live in the areas that might have to be evacuated to insure radiological safety and that most of these are concentrated in coastal villages, on offshore islands, and along the major streams. All of these people are dependent on shifting agriculture, hunting in the forests, and fishing in the streams or estuaries near their homes. They live in proximity to the proposed canal routes and are almost entirely dependent upon their immediate bioenvironment. If the areas in which these people live were contaminated by radioactive fallout, they would be exposed not only to external radiation, but also to internal radiation due to the entry of radionuclides into the agricultural, forest, freshwater, estuarine, and marine ecosystems on which they depend for food, water, and other materials essential to their culture.

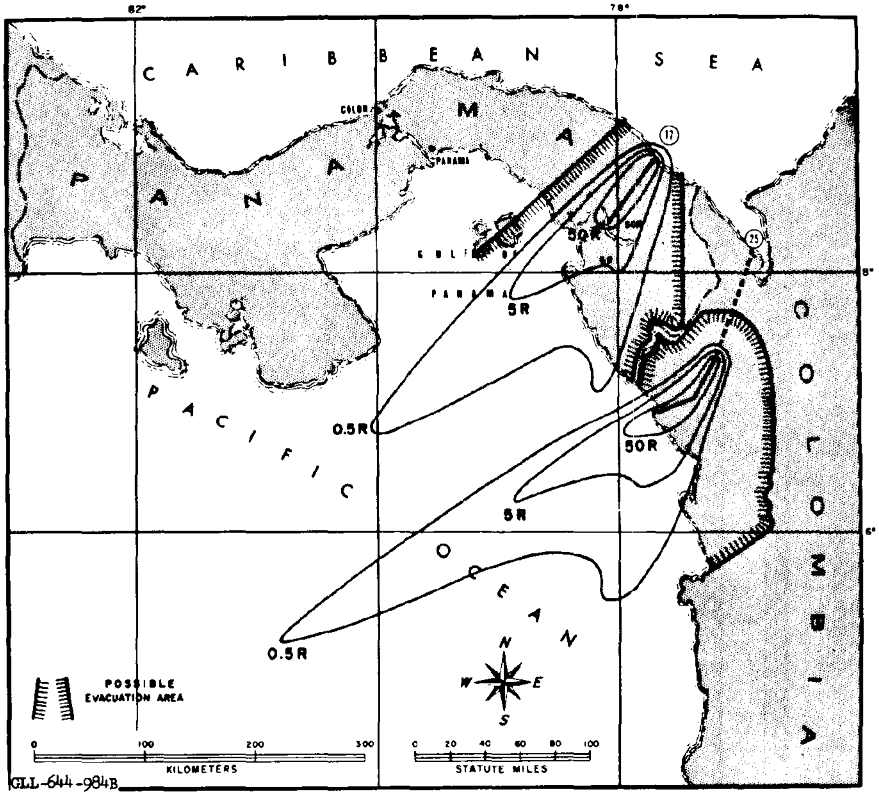

Fig. 2. Possible evacuation zones and fallout patterns (lifetime dose) for Routes 17 and 25.

One plan to insure the radiological protection of indigenous populations calls for control measures to insure that essentially all of the local fallout is deposited in a prescribed area from which all people, except those working on the canal, are excluded at least until sometime after the nuclear excavation is completed. Figure 2 shows a preliminary estimate, based on the same wind conditions for all detonations, of what the composite fallout patterns might look like and indicates the approximate boundaries of appropriate exclusion areas. These hypothetical fallout patterns indicate the potential gamma exposure dose at infinite time, and the boundaries of the exclusion areas are so arranged that no person outside the exclusion area would be exposed to an external gamma dose of more than 0.5 R. The calculations leading to the preparation of Fig. 2 were based on the nuclear technology of 1964, and present technology indicates that the release of radioactive materials could be even further reduced. The predicted release of radioactive materials is classified, but, for planning purposes, the AEC has said that, "For each individual nuclear explosive detonated, the sum of fission products airborne in the radioactive cloud and in the fallout release may be as low as the equivalent of 20 tons. The tritium release may be less than 20 kilocuries per kiloton of total yield."

What this may mean in terms of gamma exposure doses can be seen in Fig. 3, in which the preliminary, composite fallout pattern for Route 17 has been superimposed on the composite fallout pattern around the AEC's Nevada Test Site. Note that the Route 17 pattern fits comfortably inside the NTS pattern, indicating that the potential radiation hazard of nuclear canal evacuation may be less than that associated with past testing of low-yield nuclear weapons in the atmosphere.

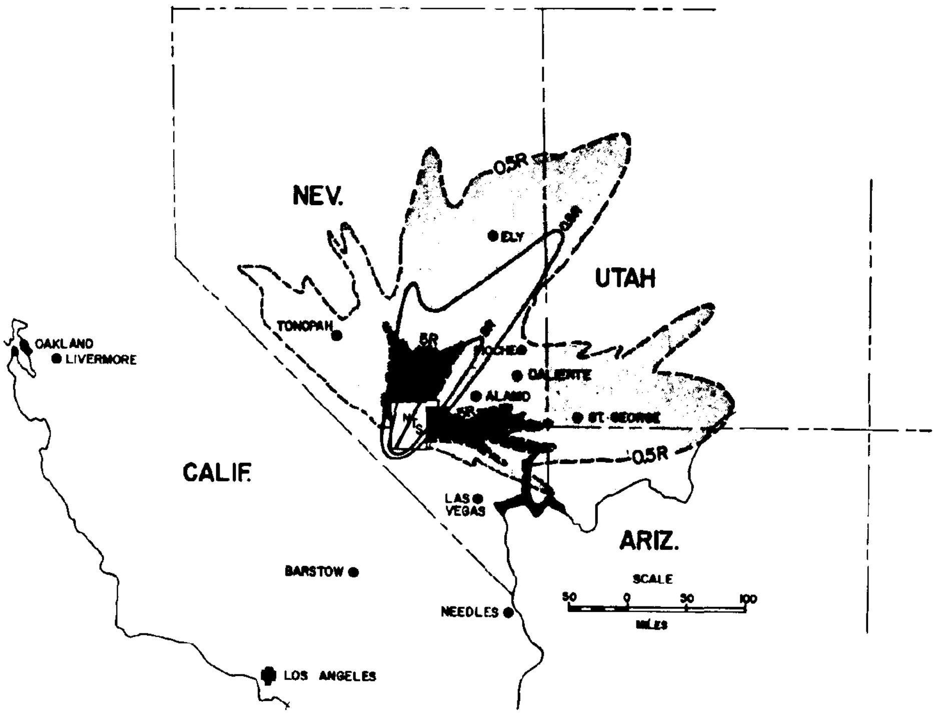

Fig. 3. Integrated lifetime doses in vicinity of Nevada Test Site compared with integrated lifetime dose resulting from nuclear excavation of Route 17.

While this picture is optimistic as far as radiological-safety feasibility is concerned, it is far from complete. There are a great many uncertainties concerning the predicted release of radioactive materials from massive nuclear-excavation detonations, and there are further uncertainties concerning the fallout patterns to be expected from each detonation. As far as the evaluation of potential internal doses is concerned, the greatest uncertainties are those related to ecology, the food chains, and other pathways leading to man. We know a great deal less about the ecology and radioecology of tropical ecosystems than we do about those of the temperate zone, of which we know all too little.

Principal Objectives of Bioenvironmental Studies

As a prime contractor to the AEC, the Battelle Memorial Institute, Columbus Laboratories, is responsible for the preparation of a final report on which a judgment can be based concerning the radiological-safety feasibility of the nuclear-excavation plan for sea-level canal construction. Included in this responsibility is the evaluation and interpretation of all available data having a bearing on the question of radiological-safety feasibility and on the technical planning and management of on-site studies required to obtain the data necessary for making estimates of potential radiation dosage to human populations.

It was decided rather early in the developmental stage of the program that, no matter what standards, guidelines, or protective actions may be adopted to insure the radiological-safety of human populations living near the proposed route for nuclear canal excavation, the radiological-safety feasibility of the project cannot be adequately judged without estimating the potential external and internal radiation doses to human populations and individuals. Other potential problems of a biological nature, such as the environmental disturbance to be expected immediately adjacent to the canal route and the possible mixing of marine species previously separated by the isthmus, were not ignored; but they were considered to be of lesser importance to the feasibility study, because such problems would be expected even if the sea-level canal were constructed by conventional means.

The principal objectives of the Bioenvironmental and Radiological-Safety Feasibility Studies under Battelle-Columbus management were stated as follows: (a) to estimate the potential external and internal radiation doses to human populations and individuals in those areas most likely to be affected by the proposed nuclear excavation, (b) to compare the estimated doses with existing standards and guidelines established for radiological safety by the ICRP (International Commission on Radiological Protection) and other such authorities, and (c) to evaluate and make recommendations concerning the potential need for and the probable effects of protective actions such as evacuation and resettlement, which may be required to insure the radiological safety of indigenous human populations or to minimize their exposure to external and/or internal radiation.

Basically, four kinds of information are required to achieve the first of the three objectives indicated above: (1) Estimates are needed of the kinds and quantities of radionuclides that would be produced by the detonations and redeposited as fallback and throwout in or near the canal channel, or would be suspended in the atmosphere and become available for wider distribution as fallout or rainout. (2) Meteorological data are required to provide predictions of rainout and fallout patterns, estimates of external gamma-exposure doses, and estimates of the initial geographical distribution of those radionuclides which are likely to account for the major part of the potential internal radiation dose to man. (3) Dietary and bioenvironmental data are required to define the pathways leading to man, and if possible, to estimate the rates of radionuclide redistribution by physical and biological processes; to estimate the probable concentrations or specific activities of critical radionuclides in drinking water, foods, and other materials of local origin that are utilized by local populations or exported for use elsewhere; and to estimate the amounts of critical radionuclides that could be ingested by people living in any part of the area close to the route of nuclear canal excavation. (4) Data to estimate internal doses to critical organs, if the amount of radionuclide ingestion is known, are readily available in the reports of the ICRP and other publications.

The data indicated in (1) have been provided by studies made at the Lawrence Radiation Laboratory and at Battelle's Columbus Laboratories. In conjunction with the fallout-pattern predictions being prepared by ESSA (2), these data will enable us to estimate the initial specific activity of the fallout produced by any given detonation and the deposition rates of individual radionuclides in pCi/m^2 at a given reference time, in areas corresponding to different external gamma dosage or dose-rate contours. The field studies related to human, agricultural, forest, freshwater, and marine ecology that have been carried out are all related to (3). The data provided by field studies will be used by Battelle to develop methods for estimating the potential quantities of radionuclides that could be ingested by people living in different parts of the study areas.

Dose Estimation

Methods and procedures for estimating dosage on the basis of input data to be provided by Battelle have been developed in the Health Physics Division, Oak Ridge National Laboratory, under the direction of E. G. Struxness. The generalized model for estimating external or internal dose due to a particular radionuclide is illustrated by Eq. 1:

$$D_i = Y_i f_i \int_{t_1}^{t_2} C_i(t)\, P_i(t)\, dt \text{ (rem)} . \tag{1}$$

The subscript i indicates the dependence of dose equivalent on a particular radionuclide and a particular exposure pathway.

The fallout input term, $Y_i f_i$ (radionuclide yield × fraction deposited at a particular location), will be provided for each radionuclide in units of radioactivity per unit area of surface by interpretation of predictions of radionuclide production and fallout deposition.

The dose commitment, C_i, is the dose rate due to a unit intake or external exposure unit of the radionuclide in question. It is shown as a function of time, because the interval t_1 to t_2 may extend over a period of years and C_i may change, due to variations in assimilation and elimination rates, organ size, etc., as the individual ages.

The pathway of exposure, $P_i(t)$, is the term about which the least is known at the present time. The most important pathways of external exposure will probably be exposure to the overpassing vented material and exposure to fallout material on land and forest canopies. The critical internal pathways may include inhalation, but the ingestion of contaminated water and foods, including agricultural products, fish, and terrestrial animals, will be more important. Field studies in the areas of human, agricultural, forest, freshwater, and marine ecology and hydrological modeling studies were undertaken to better define the important pathway terms, $P_i(t)$, for the stable elements corresponding to the potentially critical radionuclides.

Potentially Critical Nuclides

Preliminary studies to identify the potentially critical radionuclides were undertaken by Battelle-Columbus Laboratories (BCL), the Lawrence Radiation Laboratory (LRL), the Oak Ridge National Laboratory (ORNL), and the Puerto Rico Nuclear Center (PRNC). The study made by PRNC involved estimates of the maximum likely specific activities of the fallout. These estimates were then used to calculate the amounts of seawater that would be needed to dilute the fallout to acceptable levels. This procedure, which was based on unclassified data, indicated that ^{3}H, ^{90}Sr, ^{54}Mn, ^{45}Ca, ^{89}Sr, ^{46}Sc, and ^{32}P are the radionuclides most likely to be critical as far as the marine environment is concerned. The assumptions and procedures followed by BCL, LRL, and ORNL were different in many respects, but they all involved the comparison of classified predictions of radionuclide production with the dose that would result from the intake (and/or external exposure to) of a unit of each radionuclide. All of these studies indicated that ^{3}H is potentially the most important radionuclide and that ^{90}Sr should be included in the top three. The other radionuclides likely to be of significant importance include ^{45}Ca, ^{54}Mn, ^{55}Fe, ^{89}Sr, ^{106}Ru, ^{131}I, ^{137}Cs, ^{144}Ce, ^{181}W, ^{210}Pb, and ^{239}Pu, but not necessarily in that order. All of these studies suggest that as much as 95 percent of the total internal dosage might be due to only 5 or 6 of the more than 300 radionuclides that could be produced by the nuclear detonations.

On the basis of these studies and other considerations, soil, water, and food samples are being analyzed to obtain basic information concerning the natural distribution and concentration of the following elements in different pathways: H, Ca, Sr, Ce, K, Cs, Ru, W, Mn, and Fe. At the same time, supplementary information will be obtained for Mg, Al, Zn, Na, N, Mo, Co, and a few other elements such as Sc, S, and C. Selected samples have been analyzed by gamma spectrometry and by radiochemistry for ^{90}Sr, but the current levels of environmental radioactivity in the study area are so low that these data will not contribute much to the assessment of potential radiological hazards related to canal construction.

Human Ecology

Studies of human ecology have been made in Panama under the direction of Dra. Reina Torres de Araúz, who is associated with the University of Panama. Similar studies of the Colombian study area were made under the direction of Lic. Alfredo Costales S. by the Ecuadorian Institute of Anthropology and Geography. The studies completed by these two groups are remarkably comprehensive, considering the short time available to them, for they have considered virtually all aspects of cultural anthropology and have summarized nearly all the available demographic data for the various cultural groups including Negroes, Choco Indians, Cuna Indians, and recent colonists from other parts of Panama and Colombia.

Of particular interest in relation to the radiological-safety program are the dietary data obtained for human groups in different parts of the study area by field investigators who lived for weeks or months in the communities being studied. As might be expected, the menus include hundreds of different items and the diets of individuals vary in relation to cultural affinity, geographical location, time of year, and other factors; but a large proportion of the total diet in any given location is composed of a few staples such as banana, plantain, corn, rice, coconuts, other fruits, and root crops. Banana and plantain are important dietary constituents almost everywhere. They are consumed raw, baked, in the ashes of a wood fire, boiled in stews with other items, or, more commonly, they are the major ingredient of beverages such as chucula, which consists primarily of river water, boiled plantain or banana, and a little cacao for flavor. Corn also is consumed primarily in the form of beverages known as chicha, which may or may not be fermented, depending on the occasion. Both lowland and upland rice are grown, and in many localities rice is considered to be a prestige food on a par with imported sardines and peanut butter or oatmeal. Fish, crustaceans such as freshwater shrimp, and mollusks are regularly taken from the rivers and little of them is discarded, except the viscera and scales of the larger fish. Except for certain predatory birds, amphibia (some of which are poisonous), and most reptiles (except turtles and iguana), virtually every kind of animal is a potential candidate for the stewpot. Except in coastal areas, little seafood is consumed locally, but the Bay of Panama provides 12 to 15 million pounds of shrimp per year, most of which is exported to the United States. Other export items include banana, plantain, coconut, and beef. Special studies have shown that while cattle raising is of increasing economic importance to the area, very little beef or milk is consumed locally.

The detailed dietary studies made by the human-ecology field teams will enable us to describe in adequate detail the typical diets of indigenous populations in each part of the study area. The kinds and quantities of foods and beverages consumed per person per day, month, or year can be estimated with a fair degree of accuracy; and the variations related to geographical location, age, season of year, and economic status also can be evaluated. Data of this sort, in conjunction with estimates of possible radionuclide concentrations in water and in different kinds of food, are essential for making estimates of potential radionuclide intakes by humans.

Agricultural Ecology

Studies of agricultural ecology, soil-plant relationships, and related problems are being made by the University of Florida under the supervision of Dr. John F. Gamble and Dr. Hugh Popenoe. Less than 1 percent of the study area is or has been recently under cultivation, and most of the cultivated areas are adjacent to the major streams. The dominant agricultural system is shifting cultivation of the slash-and-burn type. This method of agriculture involves the cutting by ax or machete of primary or secondary vegetation. Following a period of drying, the slash is burned and the crops are planted without any prior cultivation of the soil. Details of procedure vary from place to place, but usually the first crop planted in a newly prepared field is an annual crop and this may be followed by a perennial crop. After a period of 2 to 5 years of cultivation, fields are allowed to revert to secondary vegetation and may be cultivated again after a period of from 6 to 20 years of "rest." The principal annual crops are corn and upland rice (some 12 or more varieties), while the principal perennial crops are banana, plantain, and coconut. A few of the less important crop plants are lowland rice, yuca, ñame, avocado, sugarcane, and cacao. A complete list of cultivated plants would probably include more than 100 species and varieties.

Riverine agriculture is important in a few areas where the rivers have terraces sufficiently large to support gardens following the flooding of the rainy season. Such fields are more or less permanent and of particular interest because of the annual deposition of river sediments, which renews the soil's fertility and may represent another mode of radioactivity entry into agricultural systems.

As mentioned earlier, there are several large cattle ranches in the study area, but nearly all of the production is intended for export and very little beef or milk is consumed locally. Also, there are a few large plantations producing coconut, plantain, banana, and a few other crops which are raised for export primarily to Panama City or to various cities in Colombia. For example, as many as 15,000 stems of plantain and banana per week may be exported from the El Real–Yaviza area to Panama City.

The agricultural ecology group has made general survey studies to characterize the major soil types and the principal agricultural systems and crops of the study area. Studies that will have been completed by the end of June, 1968, include chemical analyses of samples of all the area's major soils and crops, and of forage and cattle tissue samples to determine concentrations of stable elements listed earlier. The results will provide a basis for describing the major agricultural activities of the region and for estimating concentration or discrimination factors for important elements in major food items. The results of radioactive tracer experiments conducted in southern Florida may provide additional information related to the rates and pathways of radionuclide transfer in agricultural systems. The results of these studies can be used in making conservative estimates of maximum possible concentrations or specific activities of radionuclides in crop plants, forage plants, and cattle as a function of location in fallout fields. Reliable, less conservative estimates of radionuclide dynamics in agricultural systems probably cannot be made until appropriate tracer experiments have been made under field conditions, and such experiments cannot be conducted within the time period remaining for the feasibility study.

Forest Ecology

Studies of forest ecology in relation to radionuclide cycling and human subsistence are being made by the University of Georgia's Institute of Ecology under the direction of Drs. Frank B.

Golley and John T. McGinnis. These studies are of particular importance, not only because the human populations of the area derive a part of their food from forest plants and animals, but also because the major part of the fallout will be deposited initially in areas occupied by forest. If the forest systems are effective in retaining the radioactive materials deposited in them, relatively less of the total fallout radioactivity will become available to the agricultural, freshwater, and marine systems which will account for an even larger fraction of the total potentially available to humans.

Preliminary studies based on aerial photographs and on an application of the Holdridge system of classification were made to obtain a rough idea of the major types of forest and their areal extent. Mangrove swamps occur on both coasts, but they are more extensive on the Pacific coast, where the tidal variation is greater. The broad Chucunaque Valley and the foothills bordering it are covered by a semideciduous-forest type dominated by cuipo (*Cavanillesia plantanifolia*), a conspicuous emergent, but stands of cativo (*Prioria copaifera*) are common along the larger streams. Humid tropical and very humid subtropical-forest types are characteristic of the Serrania del Darien, which, in Panama, are parallel to the Caribbean coast. Farther south, this mountain range has a north-south orientation and the same or a very similar humid tropical-forest type occurs in a broad zone between the marshes and swamp forests of the Atrato Basin to the east and the very humid tropical-forest type which characterizes the higher ground to the west.

Hunting and gathering are less important than agriculture to the subsistence culture of the area, but they still account for a significant portion of the total diet and material culture. Hunting is done mostly during the dry season when agricultural chores are less time-consuming and animals are more readily available along the streams. Deer, tapir, peccary, monkeys, and other mammals are hunted for food and a few, such as the jaguar, ocelot, puma, and otter, are hunted for their fur. Birds such as tinamou, toucan, curassow, and chachalaca are taken for food, as are iguana, land snails, and land crabs. Wild plant species are utilized for house and boat construction, for making household utensils, for firewood, and for food, cosmetics or medicines. The weapons usually used in hunting are small-caliber rifles or shotguns and the game is usually eaten immediately. When the hunting is especially good, the surplus is preserved by smoking it over open wood fires.

To characterize the different forest types, quarter-hectare plots have been harvested to determine the biomass of upper- and lower-canopy foliage, stems, fruits, and epiphytes. Samples have been collected to determine the elemental composition of each of these forest components and of forest soils at different depths. The same kinds of analyses are being performed on samples of birds, animals, and plant foods commonly derived from the forests by people living in different parts of the study area.

The dynamic aspects (pathways and rates of chemical transfer) are being studied by three methods: (1) analyses of litter-fall samples collected at intervals during the dry and rainy seasons, (2) analyses of rainfall through-fall, stemflow, and soil-water samples collected at the same locations and time intervals, and (3) stable-element (cesium) tracer experiments in the field.

The results of these studies will be used in an attempt to develop a mathematical model representing the kinetics of radionuclides in forest systems so that the potential output to man, via plants and animals utilized as food and by way of water moving into the streams and rivers, can be estimated on a time-specific basis. If this effort is unsuccessful, conservative estimates of the output to man via plants and animals can be made on the basis of concentration or discrimination factors and estimates of the output to streams can be based on simplified hydrological models.

Freshwater Ecology

Studies of freshwater ecology are being made by Battelle-Northwest Laboratories under the direction of Drs. William L. Templeton and John M. Dean to provide data which can be used in estimating the potential uptake of radionuclides via water and aquatic animals. The rivers of eastern Panama and northwestern Colombia are the major routes of travel, and the population of the area shows a definite riverine distribution pattern. Even the San Blas Islands, on which Cuna Indians live, are near the mouths of small rivers on the mainland near which they have their farms and from which they obtain their drinking water. The same can be said of coastal villages on the mainland, and all of the Negro and Cuna villages and the scattered houses of Choco Indians inland are located on river banks. The rivers provide essentially all the water used for drinking, cooking, and the preparation of beverages; and a significant fraction of the dietary protein is provided by river fish, mollusks, and crustaceans.

Working in close cooperation with the human ecology team, the freshwater ecology group have collected samples of water, sediments, and freshwater food organisms near populated areas on all the major streams and rivers in the Panama and Colombia study areas. These samples have been or are being analyzed to determine their elemental composition and the results will be used to estimate equilibrium concentration or discrimination factors for different elements in different food organisms.

The results of these studies, in conjunction with estimates of time-specific radioactivity pulses in streams provided by the hydrological modeling program (described later), will be used in making conservative estimates of maximum radionuclide concentrations and specific activities in drinking water and freshwater food organisms. For those cases in which estimates of rate parameters are available, it may be possible to base less conservative estimates on an analysis of radionuclide dynamics in freshwater ecosystems.

Hydrological Modeling

Hydrological models for the freshwater systems and for the canal channel per se are being developed by the Palo Alto Laboratories of Isotopes, Inc. (formerly Hazelton Nuclear Science Corporation), under the direction of Drs. Paul R. Fenske and Robert L. Charnell. Making use of the fallout predictions provided by ESSA, whatever rainfall data are available in the literature or are forthcoming from on-site studies, and the results of the U.S. Army Corps of Engineers on-site hydrological studies, the hydrological model will provide estimates of the time-specific concentrations of radionuclides at specified use points on different streams following pulse inputs to the watersheds from each nuclear detonation. The hydrological model for the canal will provide an estimate of the radionuclide input from the canal to the marine environment after the canal is opened at both ends. Models to describe the subsequent redistribution of radionuclides by diffusion and currents in the marine environment are being considered at Battelle-Columbus, with guidance from several consultants.

Estuarine and Marine Ecology

Studies of estuarine and marine ecology are being made by the Puerto Rico Nuclear Center under the direction of Dr. Frank G. Lowman. Samples of water, sediment, and marine organisms have been collected for chemical and radiochemical analyses at numerous stations along both the Pacific and Caribbean coasts of Panama and Colombia. The results of these studies, in conjunction with fallout predictions and estimates of the specific activities of fallout, will allow Dr. Lowman to assess the potential radiological hazard associated with the marine environment according to the methods recommended in NAS/NRC Publication 985 (1962). Subsequent to this, less conservative estimates can be based on calculations which take into account such ameliorating factors as the decrease in specific activity due to radioactive decay and to further dilution by dispersion following each nuclear detonation.

Under the direction of Dr. Gilbert L. Voss, the Institute of Marine Science at the University of Miami has prepared a detailed report on the marine resources and ecology of both the Atlantic and Pacific coasts of Panama and Colombia. Marine fishing is practiced as part of the subsistence economy on both coasts of both countries, but this activity is probably most important in the San Blas Islands, where sea fishing is almost a daily activity. As mentioned earlier, the most important commercial activity is the shrimp fishery in the Bay of Panama, which, due to seasonal upwelling, is a highly productive area. Most of the shrimp caught in this area are exported to the United States. The annual catch varies from 12 to 15 million pounds and is valued at about $7 million.

Ecological Modeling

The prime objective of all the bioenvironmental field studies under Battelle management is to provide data which will be useful in obtaining estimates of the kinds and quantities of radionuclides that might be ingested via water and foods by various kinds of people living in different parts of the study area, so that estimates of potential internal doses can be made. The most realistic kind of model that could be used for this procedure would be a coupled-compartment, dynamic model representing the transfer of radionuclides through the various links of food chains and other pathways leading to man. Water-fish-man or soil-plant-animal-man are examples of pathways that could be represented by a coupled-compartment model. The net flux of a radionuclide to a given compartment would be expressed by Eq. 2:

$$\frac{dX_j}{dt} = \sum_{i=0}^{n} \lambda_{ij} X_i - \sum_{i=0}^{n} \lambda_{ji} X_j \, . \tag{2}$$

In this example, the jth compartment is the compartment of reference. It has income and loss pathways designated ij and ji, respectively. The input terms are represented by $\lambda_{ij} X_i$, where λ_{ij} is an environmental transfer coefficient having units of reciprocal days and X_i represents the radionuclide concentrations in the ith source compartment. The details of such a model are given in the paper by Kaye and Ball (1969). The point being stressed here is that such models are not practical, unless the environmental transfer coefficients for each intercompartmental pathway are known. The best way to obtain estimates of these rate parameters is by means of radioactive tracer experiments in which the tracer is introduced into one compartment at a time. After the radionuclide in the compartment of reference has reached an equilibrium concentration, the effective loss rate can be measured directly. Such experiments are sufficiently costly and time-consuming that they could not be undertaken during the course of the feasibility study, which is limited in respect to both time and budget. Consequently, the only estimates of intercompartmental transfer coefficients available for use at this time are those reported in the literature and those that can be inferred from data collected by Battelle subcontractors.

The alternative methods of estimating possible radionuclide concentrations in foods and potential intakes by human populations or individuals are more conservative than those based on coupled-compartment dynamic models and will result, therefore, in dose estimates which are higher by some unknown factor than would realistically be expected to occur in nature. In the final analysis, the methods that can be used will depend upon the kind of data available. If, for example, the only data available were estimates of the maximum possible specific activities of the radionuclides contained in fallout, it would still be possible to make a crude estimate of potential radiological hazards by calculating the dose that would occur if the same specific activity were to occur in the human body at some initial time. This, of course, would provide an extremely conservative estimate of potential doses, because it assumes that all the radioactivity in the fallout is available for assimilation and it makes no allowances for dilution by the stable elements contained in soil, water, and foods. Other conservative estimates can be made by considering the rates of radionuclide deposition, pCi/m^2, at a given location in a fallout field and by using the concentration factors provided by field studies to evaluate the maximum possible, carrier-free concentrations of radionuclides in water and foods of various kinds. These concentrations, multiplied by quantities consumed per day, could be used to calculate the initial concentration of a given radionuclide in the total diet. In the absence of measured rate coefficients, the time-specific variation in the amount of a given radionuclide contained in the total diet would be allowed to vary as a function of radioactive decay. All these approaches are conservative, because they deliberately introduce assumptions which, if they apply at all, would apply realistically only to the worst possible cases. In view of the uncertainties concerning predictions of radionuclide production and fallout patterns and due to the scarcity of ecological data which would permit a realistic analysis of radionuclide dynamics in the potentially critical pathways leading to man, an element of conservatism in arriving at estimates of potential radiation doses seems highly desirable.

Aside from the requirements of the feasibility study, the procedures outlined in the previous paragraph will be valuable to the extent that they help to identify the important problem areas, which should receive more attention from ecologists who want their studies to be of practical value in guiding massive engineering projects that are capable of changing the face of the earth. For example, the foregoing discussion shows that the evaluation of intercompartmental transfer coefficients by means of ecosystem tracer studies should receive more attention. Such studies fall clearly in the realm of ecologists who are interested in the functional dynamics of ecosystems and in the relationship between man and his bioenvironment.

In closing, it is emphasized that only a superficial outline of a few of the problems related to radioecology and nuclear engineering has been provided in this paper. It is hoped that it has been successfully demonstrated that the assessment of radiological-safety feasibility depends upon the accumulation of ecological and biogeochemical data and the application of radioecological principles, many of which are not well known at the present time. The ultimate feasibility of nuclear canal excavation and the decision to proceed with the nuclear excavation plan or to take another course of action will be influenced by a great many considerations having nothing to do with radiological safety or biological factors. If a decision is made to proceed with the nuclear excavation plan, a number of years will pass before the construction actually begins; and one may assume that this time will be available for the further study of critical problems related to the assessment of radiological safety and of other ecological problems related to the total biological cost of the project. We are attempting to provide a scientifically sound basis for judging one aspect of the total problem – the radiological-safety feasibility of the nuclear-excavation plan – but the significant results of the initial round of studies may be the identification and definition of potentially critical problems about which more information should be sought.

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